PB84-169317

Performance and Economic Feasibility of a Sludge/Wastepaper Gasifier System

California Univ., Davis

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Mar 84

U.S. Department of Commerce
National Technical Information Service
NTIS

PB84-169317

EPA-600/2-84-063
March 1984

PERFORMANCE AND ECONOMIC FEASIBILITY OF A SLUDGE/WASTEPAPER GASIFIER SYSTEM

by

N.W. Sorbo, G. Tchobanoglous, and J.R. Goss
University of California
Davis, California 95616

and

S.A. Vigil
California Polytechnic State University
San Luis Obispo, California 93407

Grant No. CR-807-379

Project Officer

Howard Wall
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

This study was conducted in cooperation with the
University of California, Davis, California 95616

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-84-063	2.	3. RECIPIENT'S ACCESSION NO. PB84 169317
4. TITLE AND SUBTITLE Performance and Economic Feasibility of a Sludge/ Wastepaper Gasifier System		5. REPORT DATE March 1984 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) N. W. Sorbo, G. Tchobanoglous, J. R. Goss, and S. A Vigil		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of California Davis, CA 95616		10. PROGRAM ELEMENT NO. DU B-113, PE CAZ1B, B-31 11. CONTRACT/GRANT NO. CR-807379
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin., OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer: Howard Wall, (513)684-7659

16. ABSTRACT

Thermal gasification of densified sludge/wastepaper fuels has been shown to be technically feasible for the co-disposal of sludge and source-separated wastepaper. The performance and economic feasibility of a downdraft packed-bed gasifier system fueled with densified sludge/wastepaper and wastepaper fuels has been evaluated.

To assess the performance of the gasifier, a series of gasifier runs was conducted at various air input rates with the use of various densified fuels. In eight of the runs, a densified fuel consisting of 20 percent lagoon-dried sludge and 80 percent recycled wastepaper was used; in five runs densified wastepaper cubes were used. Gaseous and particulate emissions resulting from the combustion of producer gas were measured. Char, a by-product of the gasification process, was evaluated as a substitute for powdered activated carbon. The performance of a small dual-fuel diesel engine combusting producer gas generated from the gasification of densified wastepaper was also demonstrated.

The cost of sludge disposal in a sludge-wastepaper gasification system, using wood chips as an auxiliary fuel was found to be competitive with the cost of sludge disposal by landfilling if the electricity generated by the gasification system can be sold at a cost of $0.12/kWh, $0.09/kWh, and $0.085/kWh for communities sizes of 10,000, 30,000, and 50,000 persons respectively.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Wastewater	Char	Sludge Disposal	
Sludge	Activated Carbon	Paper-Sludge Disposal	
Combustion		Producer Gas	
Incineration		Duel-Fuel Diesel Engine	07C
Gasification			
Air Pollution			
Co-incineration			

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 195
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE

EPA Form 2220-1 (9-73)

DISCLAIMER

Although the information described in this article has been funded wholly or in part by the United States Environmental Protection Agency through assistance agreement number CR-807379 to University of California, Davis, California, it has not been subjected to the Agency's required peer and administrative review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communications link between the researcher and the user community.

Development of safe and economical methods for disposing of the sludges produced from wastewater treatment operations is one of the most pressing environmental needs. This publication provides much needed information on the feasibility of one approach to dispose of sludge and municipal solid wastes and at the same time generate a gas that can be used to reduce the need for priority fuels.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Thermal gasification of densified sludge/wastepaper fuels has been shown to be a technically feasible method for the co-disposal of sewage sludge and source-separated wastepaper. The research discussed in this report deals with an evaluation of the performance and economic feasibility of a downdraft packed-bed gasifier system fueled with densified sludge/wastepaper and wastepaper fuels.

A pilot-scale batch-fed downdraft gasifier was used to convert densified sludge/wastepaper and wastepaper fuels into a low-energy combustible gas (producer gas) and char. The fuel flow in the downdraft gasifier was by gravity, with the air and fuel moving co-currently through the gasifier. The producer gas was composed of nitrogen, carbon monoxide, hydrogen, water vapor, carbon dioxide, methane, and other hydrocarbon gases. The char was composed primarily of carbon and inert residue.

A series of gasifier runs was conducted using a densified fuel consisting of 20 percent dewatered sludge and 80 percent recycled wastepaper. The efficiency of producing cold, dry producer gas from the densified sludge/wastepaper fuel varied between 43 and 72 percent. The dry producer gas energy content varied between 4.84 and 5.49 MJ/m^3. Prohibitive slag formations were not produced in the gasification of the sludge/wastepaper fuels tested.

The performance of a small dual-fuel diesel engine using producer gas generated from the gasification of densified wastepaper was demonstrated. The practical output of the dual-fuel diesel engine operated with producer gas was 71 percent of the engine power output operated with diesel fuel alone. Emission tests from the combustion of producer gas in a burner system were conducted. The federal particle emission standards for incinerators were met for the combustion of producer gas in the burner system without the use of flue clean-up equipment. Char produced as a byproduct of the gasification process was evaluated as a substitute for powdered activated carbon. The production of char as a suitable substitute can be accomplished only if the gasifier is operated inefficiently.

A sludge/wastepaper gasification system using wood chips as an auxiliary fuel was found to be competative with the cost of sludge disposal by landfilling if the electricity generated by the gasification system can be sold at an average cost of \$0.12/kWh for communities of 10,000 persons, \$0.09/kWh for communities of 30,000 persons, \$0.085/kWh for communities of 50,000 persons. The economic feasibility of sludge/wastepaper gasification is sensitive to the cost of wood chips, the solids content of the dewatered sludge, the percentage of wastepaper collected, and the resale value of electricity.

This report was submitted in fulfillment of Contract No. CR-807-379 by the University of California, Davis under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period October 28, 1980 to July 28, 1982.

CONTENTS

Foreword iii
Abstract iv
Figures vii
Tables x
Metric Conversion Factors xii
Acknowledgements xiii

1. Introduction 1
    The Gasification Process 1
    Sludge/Wastepaper Gasification for Small Communities 5
    Conclusions from Previous Sludge/Wastepaper Gasification Work 7

2. Conclusions and Recommendations for Future Research 8
    Conclusions. 8
    Recommendations for Further Research. 9

3. Experimental Apparatus, Methods, and Procedures 11
    Experimental Gasification System. 11
    Laboratory Testing 20
    Field Testing. 20
    Preparation of Gasifier Fuels 25
    Operation Procedures 26
    Mass and Energy Balance Computations. 27

4. Experimental Results 28
    Gasifier Run Summaries. 28
    Operating Data. 28
    Mass and Energy Balances. 38

CONTENTS (continued)

5. Discussion 46

  Evaluation of Gasifier Performance 46
  Air Pollution Emission Tests 59
  Feasibility of Using Gasifier Char as a Source of Powdered Activated Carbon 63
  Operation of a Small Diesel Engine with Producer Gas 68

6. Economic Feasibility of Sludge/Wastepaper Gasification in Small Communities. 70

  Sludge/Wastepaper Gasification System Description 70
  Economic Analysis 76

References 88

Appendices 93

  A. Mass and Energy Balance Computations 93
  B. Computer Program Listing and Output Data for the Mass and Energy Balances. 108
  C. Analysis of Gasifier Samples for Metals 133
  D. A Summary of the Draft Report prepared by Engineering Science, Emission Testing of University of California, Davis Sludge Gasifier 136
  E. Computer Program Listings and Input Data for "PAPCOLLCOST" and "GASFEASSTDY" 160

FIGURES

Number		Page
1.	Schematic of a downdraft gasifier	4
2.	Process diagram for a sludge/wastepaper gasification system	6
3.	Schematic diagram of the UCD sludge/wastepaper gasification system	12
4.	Cross-section - UCD sludge/wastepaper gasifier	13
5.	Exterior view - UCD sludge/wastepaper gasifier	14
6.	Interior view - UCD sludge/wastepaper gasifier	14
7.	Interior dimension symbols for a downdraft gasifier firebox	16
8.	Data analysis subsystem for monitoring gasifier operation.	18
9.	Producer gas burner system	19
10.	Schematic diagram of the Papakube densification system.	21
11.	Producer gas analysis sample train	24
12.	Producer gas analysis system	24
13a.	Phase diagram for a CaO-Fe_2O_3-SiO_2 system	37
13b.	Phase diagram for a CaO-FeO-SiO_2 system	37
14.	Producer gas composition and temperature profile for Run 28-A	41
15.	Producer gas composition vs. air input rate	48
16.	Equilibrium curve for methane at 1 atmosphere pressure.	53
17.	Gasifier efficiencies vs. air input rate	54

FIGURES (continued)

Number		Page
18.	Equilibrium curve for Boudouard's reaction at 1 atmosphere pressure	55
19.	Process diagram of a sludge/wastepaper gasification system for a small community	71
20.	Variation of the percent ash in a sludge/wastepaper mixture as a function of the percentage of wastepaper collected	74
21.	Quantity of wood chips that need to be added to the sludge/wastepaper mixture to maintain an ash content of 5 percent	75
22.	Quantity of wood chips that need to be added to the sludge/wastepaper mixture to maintain a moisture content of 20 percent	77
23.	Quantity of wood chips added to the sludge/wastepaper mixture to maintain an ash content of 5 percent and a moisture content of 20 percent	78
24.	Sensitivity of the net total annual cost of a sludge/wastepaper gasification system to the wood chip and power costs for a community of 10,000 persons	85
25.	Sensitivity of the net total annual cost of a sludge/wastepaper gasification system to the wood chip and power costs for a community of 30,000 persons	86
26.	Sensitivity of the net total annual cost of a sludge/wastepaper gasification system to the wood chip and power costs for a community of 50,000 persons	87
A-1	Overall mass balance	97
A-2	Nitrogen mass balance	97
A-3	Hydrogen mass balance	99
A-4	Oxygen mass balance	99
A-5	Carbon mass balance	101
A-6	Condenser energy balance	105
D-1	Anderson 2000 6-stage impactor particle size results: producer gas	143

FIGURES (continued)

Number Page

D-2 Anderson 2000 6-stage impactor particle size results: stack outlet 144

D-3 UCD sludge gasifier. 145

TABLES

Number		Page
1	Internal Dimensions of UCD Civil Engineering Sludge/Wastepaper Gasifier	17
2	Summary of Data Collection and Analysis Equipment	22
3	Fuel Summary	30
4	Char Summary	31
5	Operational Summary	33
6	Analysis of Metals in 20 Percent Sludge/Wastepaper Fuel and Char	36
7	Composition and Energy Content of Producer Gas	39
8	Mass and Energy Balances for Gasifier Runs 14 through 28-B	42
9	Modifications of Producer Gas Flowrates Measured by Engineering Science	60
10	Particle Emission Rates from the Producer Gas Burner	62
11	Correction of Particle Size Distribution Data	64
12	Chemical Composition of Gasifier Chars used in Activated Carbon Studies	66
13	Summary of Adsorption Characteristics of Powdered Activated Carbons and Gasifier Chars	67
14	Annual Cost for Sludge Disposal by Landfilling	81
15	Important Assumptions for the Economic Analysis of a Sludge/Wastepaper/Wood Chip Gasification System	82
16	Equipment Capital Cost for Sludge/Wastepaper/Wood Chip Gasification System	83
A-1	List of Mass Balance Terms	94

TABLES (continued)

Number Page

A-2 List of Energy Balance Terms 103

C-1 Description of Gasifier Samples for PIXE Analysis. 134

C-2 Output Data from PIXE Analysis of Sludge/Wastepaper Gasifier Samples. 135

D-1 Schedule of Testing Conducted on U.C. Davis Sludge Gasifier 137

D-2 Particulate Emissions Summary - U.C. Davis Sludge Gasifier and Burner 138

D-3 Summary of NO_x and Noncondensible Hydrocarbon Measurements, Burner Outlet Stack - U.C. Davis Sludge Gasifier 140

D-4 Summary of SO_2 Test Results, U.C. Davis Sludge Gasifier 141

D-5 Characterization Sample Collection, July 16, 1981 141

E-1 Input Variables for Computer Program "PAPCOLLCOST" for Calculation of Wastepaper Collection Costs for a Sludge/Wastepaper Gasification System 174

E-2 Wastepaper Collection Costs. 176

E-3 Input Variables for "GASFEASSTDY" used to Calculate Costs for Sludge/Wastepaper Gasification System 177

METRIC CONVERSION FACTORS

Factors for the conversion of U.S. Customary Units used in this report to the International System (SI) of Units

Multiply the U.S. customary unit		By	To obtain the corresponding SI unit	
Name	Abbreviation		Name	Symbol
Atmospheres	atm	101300	Newtons per square meter	N/m^2
British thermal units per pound	Btu/lb	2.326	Kilojoules per kilogram	kJ/kg
Cubic foot	ft^3	0.0283	Cubic meter	m^3
Cubic yard	yd^3	0.7646	Cubic meter	m^3
Degree Celsius	^oC	plus 273	Degree Kelvin	^oK
Degree Fahrenheit	^oF	0.555 (^oF-32)	Degree Celsius	^oC
Gallon	gal	3.785	Liter	ℓ
Grains per cubic foot	gr/ft^3	2.29	Grams per cubic meter	g/m^3
Inch	in	0.0254	Meter	m
Mile	mi	1.609	Kilometer	km
Pounds (mass)	lb	0.4536	Kilogram	kg
Square foot	ft^2	0.0929	Square meter	m^2
Ton (2000 pounds mass)	ton	907.2	Kilogram	kg
Watt-hour	Wh	3.60	Kilojoule	kJ

ACKNOWLEDGEMENTS

The assistance of the following persons is gratefully acknowledged: A. Kaupp, R. Couper, G. Lamorey, J.J. Mehlschau, N. Raubach, and G. Ginnini of the Department of Agricultural Engineering, University of California, Davis; M. Abramson and K. Fattahi of the Department of Mechanical Engineering, University of California, Davis; D.A. Bartley and D. Davis; G.B. Nelson and G.C. Nelson of the Papakube Corp., R. Sachs of the Department of Environmental Horticulture, University of California, Davis; and R. Gertman of Davis Waste Removal Co. This report was typed by D. Pfoutz.

SECTION 1

INTRODUCTION

The disposal of sewage sludge in an economic and environmentally acceptable manner is a problem faced by all communities that have municipal wastewater treatment facilities. Similarly, all communities are faced with the disposal of increasing quantities of solid wastes. The co-disposal of sewage sludge and solid waste in a joint facility is an acceptable solution to both of these problems. But, the trend in the development of such projects has been towards very large systems to provide the economy of scale that is presumed necessary.

A new process for the co-disposal of sewage sludge and wastepaper that is feasible for small communities was introduced by Vigil (61). The process involves the gasification of densified mixtures of sludge and source-separated wastepaper in a simple packed-bed reactor using air as the oxidant. Energy in the form of producer gas, which is produced in the gasification process, can be used to fuel boilers, heaters, engines, or turbines.

The continuing development of the sludge/wastepaper gasification process introduced by Vigil (61) is presented in this report. A brief review of the results of previous sludge/wastepaper gasification research is presented in this section.

THE GASIFICATION PROCESS

Gasification is an energy efficient technique used to produce low-energy gas and reduce the volume of the fuel. The gasification process involves the partial combustion of a carbonaceous fuel to generate a combustible gas rich in carbon monoxide, hydrogen, and some saturated hydrocarbon gases, principally methane. A brief review of the gasification process is given here.

Definition

Gasification involves the partial combustion of a carbonaceous fuel to generate a combustible gas containing carbon monoxide, hydrogen, and gaseous hydrocarbons. Currently much confusion exists in the literature between the terms "pyrolysis" and "gasification." In this report, the following definitions given by Lewis (33) are used.

> Pyrolysis - Thermal processing of waste in the absence of oxygen, in (a) indirectly heated retorts, and (b) furnaces that are directly heated by fuel gases from a burner firing on a stoichiometric air/fuel ratio.

Gasification - Thermal processing of waste where a fraction of the stoichiometric oxygen required by the waste is admitted directly into the fuel bed to liberate the heat required for endothermic gasification reactions. The volatile portion of incoming waste will be pyrolyzed by the heat of the fuel gases, and the outlet gas composition will reflect both processes.

Historical Development

Gasifiers have been used since the 19th century. The first coal gasifiers were built by Bischof in Germany in 1839, by Ebelman in France in 1840, and by Ekman in Sweden in 1845. This early development was followed by the Siemens brothers in Germany in 1861. The Siemens' gasifiers were used primarily to fuel heavy industrial furnaces. The development of gas cooling and cleaning equipment by Dowson in England in 1881 extended the use of gasifiers to small furnaces and gas engines (43).

By the early 1900's, gasifier technology had advanced to the point where most ligno-cellulosic materials such as wood, fruit pits, straw, and walnut shells could be gasified. These early gasifiers were used primarily to provide fuel for stationary gasoline engines. Portable gasifiers also emerged in the early 1900's. They were used for ships, automobiles, trucks, and tractors. The real impetus for the development of portable gasifier technology was World War II. During the war years, France had more than 60,000 charcoal-burning cars, and Sweden had about 75,000 wood-burning, gasifier-equipped buses, cars, tractors, and engine-powered boats. With the return of relatively cheap and plentiful gasoline and diesel oil after the end of World War II, gasifier technology was all but forgotten. In Sweden, however, research has continued into the use of wood fueled gasifiers for diesel tractors and transport trucks. (39). Furthermore, the downdraft gasification of peat is being pursued actively in Finland (25).

Although considerable success has been reported with the gasification of charcoal, coal, wood, and certain agricultural wastes (9,17,34,44,64,65,66), the gasification of solid waste has not been as successful. A recent editorial in a leading solid waste trade magazine (52) stated that pyrolysis [i.e., gasification] systems such as the Union Carbide Purox System, the Landguard System, and the Occidental Flash Pyrolysis System have been technical and economic failures. The principal causes for the failure of gasification technology in the solid waste field has been the complexity of the systems and a lack of appreciation for the heterogeneous nature of solid waste, mixed with air-dried sludge. The approach taken in this research was to use the simplest reactor possible (the vertical packed-bed gasifier) and to fuel it with the cleanest form of solid waste (source-separated wastepaper). An in-depth review of current research into pyrolysis and gasification systems of solid wastes is presented by Jones (27) and Jones et al. (28).

Reactor Types

The four basic types of reactors used in gasification are: 1) verticle packed-bed, 2) multiple hearth, 3) rotary kiln, and 4) fluidized bed. Most of the early gasification work in Europe was with the air-blown, packed-bed reactors.

The vertical, packed-bed, downdraft reactor has a number of advantages over the other types, including simplicity and relatively low capital cost. But it is more sensitive to the mechanical characteristics of the fuel. The merits and limitations of vertical packed-bed gasifiers are discussed in detail by Eggan and Kraatz (16). In a downdraft gasifier, fuel flow is by gravity, with air and fuel moving co-currently through the reactor (see Figure 1). At steady state, four zones form in the reactor. In the hearth zone, where air is injected radially into the reactor, partial combustion reactions predominate. Some heat transfers from this zone upward into the fuel mass, causing pyrolysis reactions in the distillation zone and partial drying of the fuel in the drying zone. Actual production of the fuel gas occurs principally in the reduction zone, (below the hearth zone) where endothermic reactions predominate, forming CO and H_2. The hot carbon bed in the combustion zone and upper part of the reduction zone thermally cracks many of the higher hydrocarbons, producing methane and other non-condensible hydrocarbon gases. The end products of the process are a carbon-rich char and the producer gas.

Gasification Reactions

A gasifier is basically an incinerator operating under reducing conditions. During the gasification process, five principal reactions occur:

$$C + O_2 = CO_2 + 393.8 \text{ MJ/kg-mol} \qquad \text{exothermic}$$

$$C + H_2O = CO + H_2 - 131.4 \text{ MJ/kg-mol} \qquad \text{endothermic}$$

$$C + CO_2 = 2CO - 172.6 \text{ MJ/kg-mol} \qquad \text{endothermic}$$

$$C + 2H_2 = CH_4 + 75.0 \text{ MJ/kg-mol} \qquad \text{exothermic}$$

$$CO + H_2O = CO_2 + H_2 + 41.2 \text{ MJ/kg-mol} \qquad \text{exothermic}$$

The heats of reaction shown above are evaluated at 25°C and 1 atmosphere pressure. The heat to sustain the process is derived from the exothermic reactions, whereas the combustible components of the producer gas are primarily generated by the endothermic reactions. Although the reaction kinetics of the gasification process are quite complex, the operation of air-blown, downdraft gasifiers of the type used in this research is straightforward. More detailed discussions of gasification theory and reaction kinetics are available in Gumz (19), Hoffman (21), Rambush (43), and Reed (44).

Downdraft Gasifier Constraints

Downdraft gasifiers are simple to construct and operate, but they have exacting fuel requirements including: 1) moisture content less than 20 percent, 2) ash content less than 6 percent, and 3) uniform particle size with good mechanical stability.

Because the fuel can be dried before gasification, excessive moisture can be overcome, but ash content and particle size are more difficult to handle. When the ash content is higher than 6 percent, there is sufficient ash to melt and solidify into slag (26), which can cause severe operational problems. A discussion of the

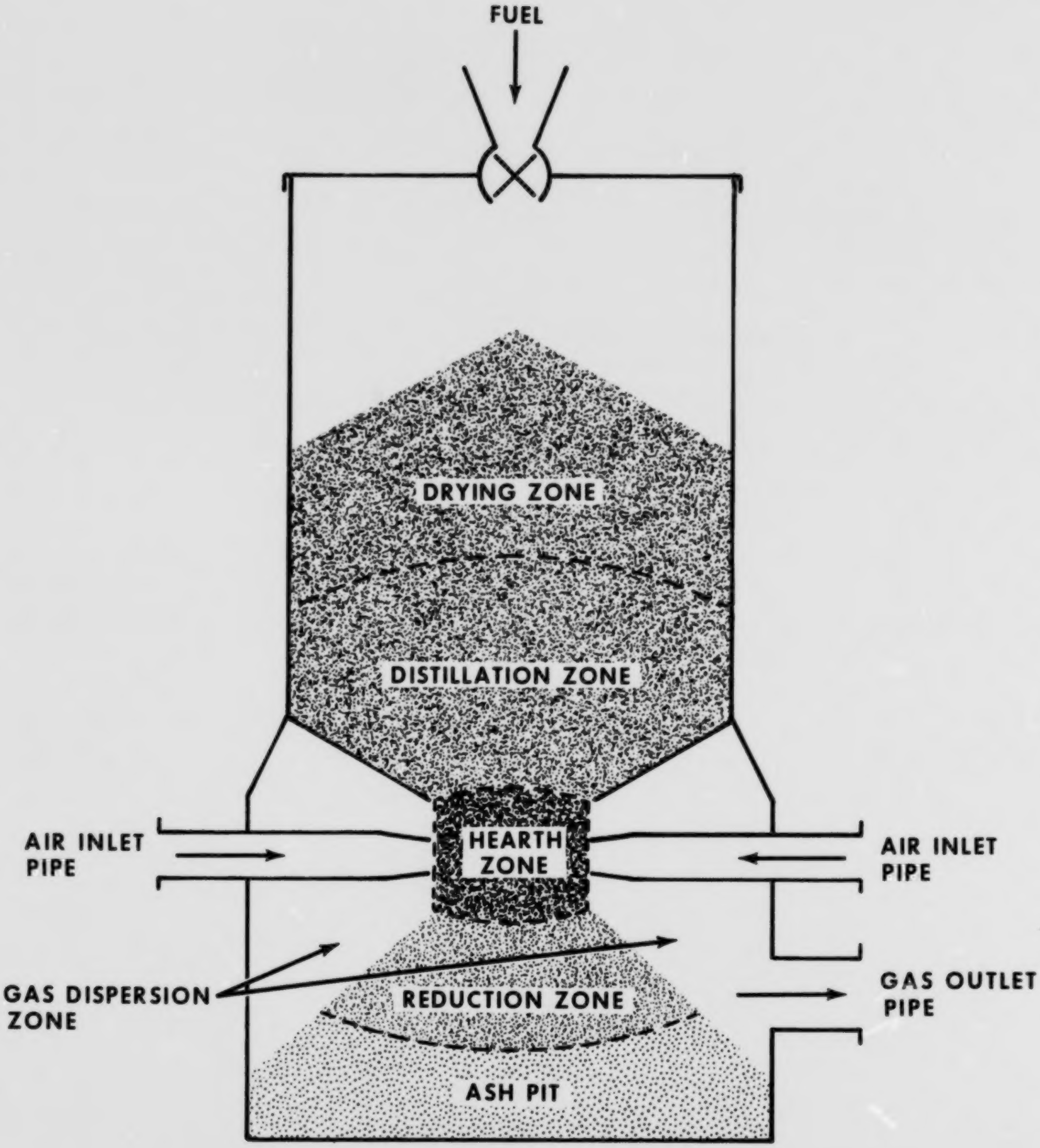

FUEL
DRYING ZONE
DISTILLATION ZONE
AIR INLET PIPE
HEARTH ZONE
AIR INLET PIPE
GAS DISPERSION ZONE
REDUCTION ZONE
GAS OUTLET PIPE
ASH PIT

Figure 1. Schematic of a downdraft gasifier.

effect of fuel ash content and other factors on the formation of slag in a downdraft gasifier is presented in Section 4. In addition, excessive fine material in the fuel can cause mechanical bridging in the fuel hopper. One method of overcoming these problems is to use more complex reactors such as a multiple hearth system or a high temperature slagging gasifiers. Although both of these approaches are operationally feasible, they are costly and complex.

A lower-cost approach is to use the simplest reactor type, the downdraft gasifier, and tailor the fuel accordingly. A suitable fuel can be made by adjusting the mixture to produce a densified refuse-derived fuel (d-RDF) that has low moisture and ash content, and uniform particle size.

SLUDGE/WASTEPAPER GASIFICATION FOR SMALL COMMUNITIES

To dispose of wastepaper and sludge in small communities, a sludge/wastepaper gasification system was proposed. A downdraft gasifier, located at the wastewater treatment plant is used to gasify a densified mixture of sludge and wastepaper, resulting in the production of a low energy gas (producer gas) and char. The chemical energy in the producer gas is converted into electricity with an engine (or gas turbine) generator set. The electricity produced is either used in the treatment plant or sold to the local power utility. A schematic diagram of a sludge/wastepaper gasification system that is applicable to small communities is shown in Figure 2.

The collection of source-separated wastepaper is one of the most important aspects of a small community sludge/wastepaper gasification system. The source separation system is designed to collect wastepaper and other recyclables efficiently without the use of large, capital-intensive, mixed-waste recovery systems. Though source separation systems are ideally suited to resource recovery in small communities, many large communities also use source separation systems.

In source separation systems, residents are requested to place bundles of newspaper, and containers with aluminum and steel cans out with their weekly trash collection. The newspaper and other recyclables are picked up by the regular collectors and carried in special containers or racks on the trash trucks. In some cities, a smaller, separate vehicle is used to collect paper and other recyclable materials. Usually, cities require that newspaper be tied into bundles. In some cities, magazines and paper bags are also collected with the newspaper. Food packaging materials are usually not recycled.

For many years, it has been assumed that the recycling of wastepaper for the manufacture of low-quality paper insulation or other products is both economically and ecologically sound. But, the high cost of energy coupled with the fluctuating markets for wastepaper are making energy recovery from wastepaper an attractive option.

In many cases only selected, clean newsprint, is suitable for recycling purposes. Source-separated wastepaper may be used more effectively in a sludge/wastepaper gasification system for the production of energy than in a wastepaper recycling system for the production of low-grade paper. Because the wastepaper recycling requirements are less restrictive when applied to a sludge/wastepaper gasification

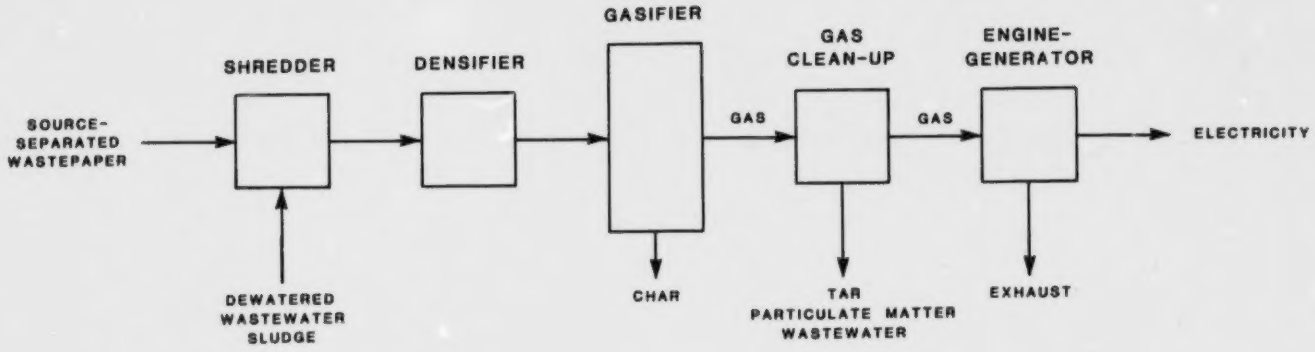

SHREDDER
DENSIFIER
GASIFIER
GAS CLEAN-UP
ENGINE-GENERATOR
SOURCE-SEPARATED WASTEPAPER
DEWATERED WASTEWATER SLUDGE
GAS
GAS
ELECTRICITY
CHAR
TAR
PARTICULATE MATTER
WASTEWATER
EXHAUST

Figure 2. Process diagram for a sludge/wastepaper gasification system.

system, a larger fraction of the solid waste generated in the community may be used.

CONCLUSIONS FROM PREVIOUS SLUDGE/WASTEPAPER GASIFICATION WORK

To test the technical feasibility of sludge/wastepaper gasification, a pilot-scale batch-fed downdraft gasifier was designed, built, and tested. Based on the original sludge/wastepaper gasification experimental work described by Vigil (61), the following conclusions were drawn:

1. The operation of a downdraft, packed-bed gasifier fueled with densified mixtures of wastepaper and wastewater sludge is technically feasible.
2. The preparation of densified sludge/wastepaper fuels at a full-scale pilot facility has been demonstrated.
3. A pilot-scale, downdraft, packed-bed gasifier was designed and constructed based on the design of agricultural waste gasifiers developed in the Department of Agricultural Engineering at the University of California, Davis.
4. The gasifier was operated with various fuels, including almond shells, wood chips, densified source separated wastepaper, and densified mixtures of sludge and source-separated wastepaper (10, 15, 20, and 25 percent sludge by wet weight). Low-energy gas (producer gas) was produced during the gasification tests, with an energy content ranging from 4.19 to 6.26 MJ/m^3 at hot gas efficiencies from 40 to 85 percent.
5. The economics of sludge/wastepaper gasification were investigated. Compared with conventional incineration, sludge/wastepaper gasification is cost effective. If mechanical sludge dewatering is used, gasification is not competative with landfilling, unless landfill one-way haul distances exceed 80 miles in communities of 30,000 persons, or 15 miles in communities of 50,000 persons. Sludge/wastepaper gasification does not appear to be a feasible option for communities of 10,000 persons.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

A series of fourteen experimental runs was conducted using a downdraft gasifier system fueled with three densified fuels. Conclusions derived from the most significant results of this work and recommendations for future research are presented below.

CONCLUSIONS

1. The gasification of densified sludge/wastewater cubes consisting of 20 percent dewatered sludge and 80 percent recycled wastepaper has been demonstrated over a series of eight test runs. The cold gas efficiency for these runs varied between 43.03 and 72.49 percent, and the dry-gas energy content varied between 4.84 and 5.49 MJ/m^3 (LHV, 25°C, 760 mm Hg). No significant slag formations occurred during the gasification of the sludge/wastepaper fuels.

2. The gasification of densified wastepaper cubes has been demonstrated over a series of five gasifier test runs. The cold gas efficiency for these runs varied between 45.37 and 60.03 percent, and the dry gas energy content varied between 4.89 and 6.02 MJ/m^3 (LHV, 25°C, 760 mm Hg).

3. The gasification of densified water hyacinth/wastepaper cubes was attempted. Because severe slagging occurred during the test run, the gasification of densified fuels containing water hyacinths grown in silt laden river waters does not seem feasible. But, the gasification of densified fuels containing water hyacinths grown in wastewater may be feasible.

4. Continuous operation of the grate throughout the gasifier run seems to reduce the formation of slag in the gasification of sludge/wastepaper fuels.

5. The operation of a dual-fuel diesel engine with producer gas generated from the gasification of densified wastepaper was demonstrated. The practical output of the dual-fuel diesel engine operated with producer gas was 71 percent of the engine output operated with diesel fuel alone.

6. Char from the gasification of certain wastepaper fuels could be used as a substitute for commercial activated carbon. However, the production of char, suitable as an activated carbon substitute, must be done at the expense of efficient gasifier operation.

7. Emission tests from the combustion of producer gas generated from the gasification of sludge/wastepaper fuels yielded the following results:

   a. Federal particle emission standards for incinerators were met without the use of flue gas clean-up equipment

   b. Concentrations of NO_x varied between 60 and 115 ppm

   c. Non-condensible hydrocarbon concentrations based on hexane were usually below 1 ppm

   d. Concentrations of SO_2 ranged from 0.037 to 0.098 grams per dry cubic meter

   e. Particle size distribution was approximately log normal with a mass median aerodynamic diameter of about 8 microns.

8. For full-scale gasification systems in a small community, an auxiliary fuel such as dried woodchips may need to be added to the sludge/wastepaper mixtures.

9. The cost of sludge/wastepaper gasification using wood chips as an auxiliary fuel is competitive with the cost of sludge disposal by landfilling if the electricity generated by the gasification system can be sold back to the local power utility at an average cost of: $0.12/kWh for communities of 10,000 persons, $0.09/kWh for communities of 30,000 persons, $0.085/kWh for communities of 50,000 persons, providing the sludge hauling distance is over 10 miles.

10. The economic feasibility of sludge/wastepaper gasification is sensitive to the cost of wood chips, the solids content of the sludge, the percentage of wastepaper collected, and the resale cost of electricity.

RECOMMENDATIONS FOR FURTHER RESEARCH

The technical feasibility of operating a downdraft gasifier with densified sludge/wastepaper and wastepaper fuels has been demonstrated. Emissions data have been gathered, a dual-fuel engine using producer gas has been tested, and the economic constraints of sludge/wastepaper gasification have been analyzed. Before full scale sludge/wastepaper gasification systems can be considered operational the following work must be done:

1. The maximum operational fuel ash content for sludge/wastepaper fuels should be determined. The effect of the air input rate, gasifier temperature, grate rotation speed, and internal gasifier dimensions on the maximum operational fuel ash content should be quantified.

2. The fate of heavy metals in the sludge/wastepaper gasification process should be determined.

9

3. Mass emission rates and particle size distributions for particulate matter in the producer gas should be measured to provide data for the design of gas cleaning equipment.

4. An investigation of the effect of lengthening the reduction zone to improve the gas quality and reduce the gas sensible heat losses should be undertaken.

5. The feasibility of using wastewater to scrub and cool the producer gas should be investigated.

SECTION 3

EXPERIMENTAL APPARATUS, METHODS, AND PROCEDURES

The experimental work described in this report was conducted on the University of California, Davis campus using the facilities, shops, and laboratories of the Departments of Civil and Agricultural Engineering. The experimental gasification system, the preparation of densified fuels, and the methods and procedures used in the collection and analysis of the data are described in this section.

EXPERIMENTAL GASIFICATION SYSTEM

To investigate the gasification of densified sludge and wastepaper, a pilot-scale gasification system was designed and constructed. The complete system consists of four subsystems: 1) batch-fed, downdraft gasifier, 2) data acquisition subsystem, 3) producer gas burner, and 4) solid waste shredder and densifier. A schematic diagram of the sludge/wastepaper gasification system developed for this project is shown in Figure 3.

Batch-Fed Downdraft Gasifier

A pilot-scale, batch-fed downdraft gasifier was designed and constructed for the experiments and is shown in Figures 4,5, and 6. The design of the gasifier is based on laboratory and pilot scale gasifiers built by the Department of Agricultural Engineering at the University of California, Davis (64,65,66).

As shown in Figure 4, the gasifier is built in three main assemblies: fuel hopper, firebox, and charpit. The fuel hopper is a double-walled cylinder. The inner wall is in the form of a truncated cone to reduce the tendency for fuel bridging. The double wall acts as a condenser to remove water vapor from the fuel before gasification. Condensed vapor is collected in a condensate gutter and drained off after each run. The fuel hopper is mounted on the firebox with quick-release clamps to allow for easy inspection after experimental runs. Because of the need for extended run lengths, a fuel hopper extension was added to the original fuel hopper. The fuel hopper extension, consisting of a circular cylinder 40.6 cm in diameter and 121.9 cm in length, is bolted to the original fuel hopper. Added to the gasifier for Runs 26, 27, 28-A, and 28-B, the fuel hopper extension is shown in Figure 3.

The firebox is also a double walled cylinder. The inner cylinder is the actual firebox. Air is supplied by four air tubes to the annular space between the walls, which acts as an air plenum to distribute air evenly to the six tuyeres (air nozzles) that supply air for partial combustion of the fuel. The choke plate acts as a large orifice, replacing the venturi section previously used in earlier World War II and Swedish gasifier designs. The firebox assembly is flange mounted to the charpit.

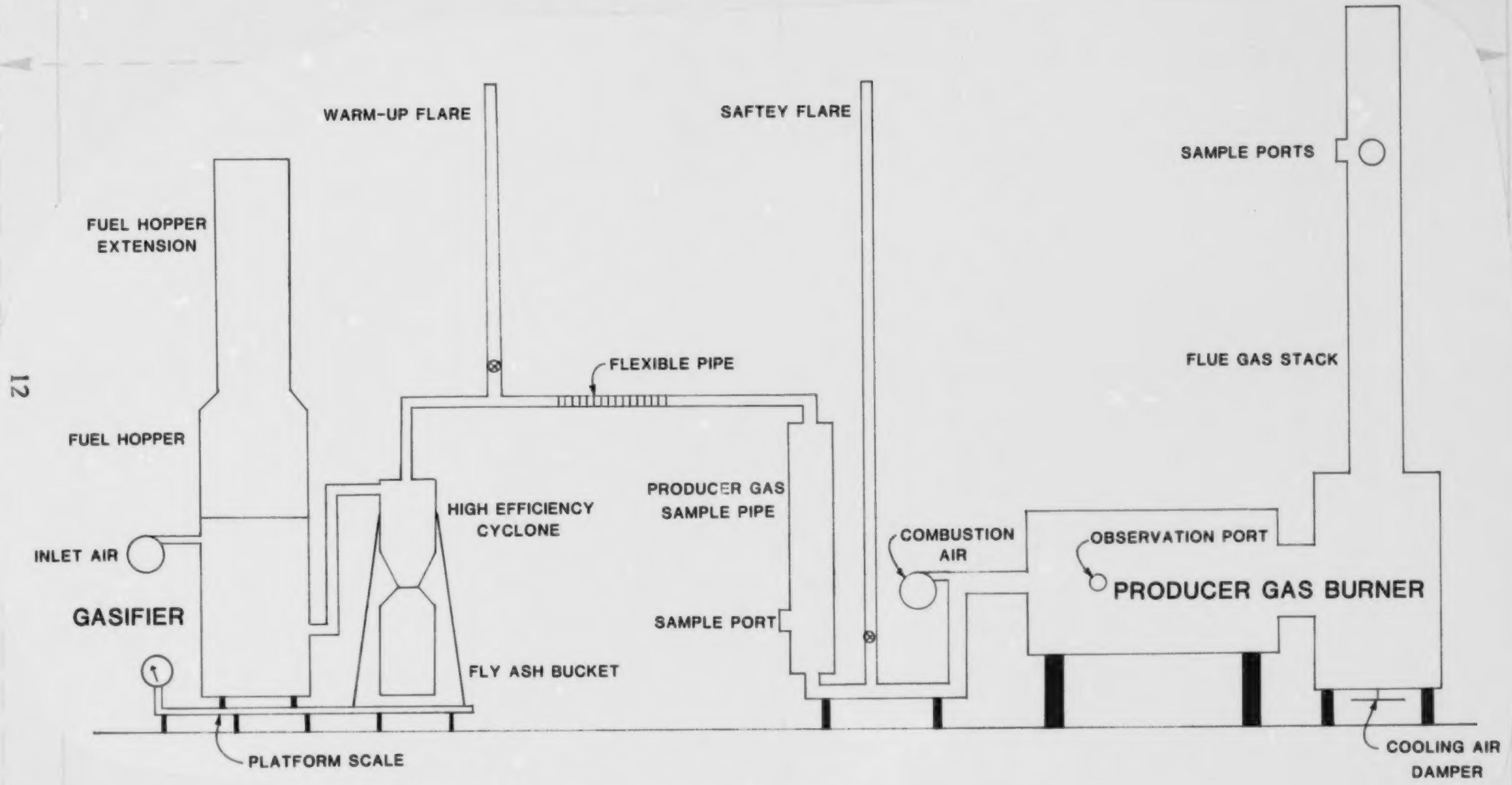

WARM-UP FLARE
SAFTEY FLARE
SAMPLE PORTS
FUEL HOPPER EXTENSION
FLEXIBLE PIPE
FLUE GAS STACK
FUEL HOPPER
HIGH EFFICIENCY CYCLONE
PRODUCER GAS SAMPLE PIPE
COMBUSTION AIR
OBSERVATION PORT
INLET AIR
PRODUCER GAS BURNER
GASIFIER
SAMPLE PORT
FLY ASH BUCKET
PLATFORM SCALE
COOLING AIR DAMPER

Figure 3. Schematic diagram of the UCD sludge/wastepaper gasification system.

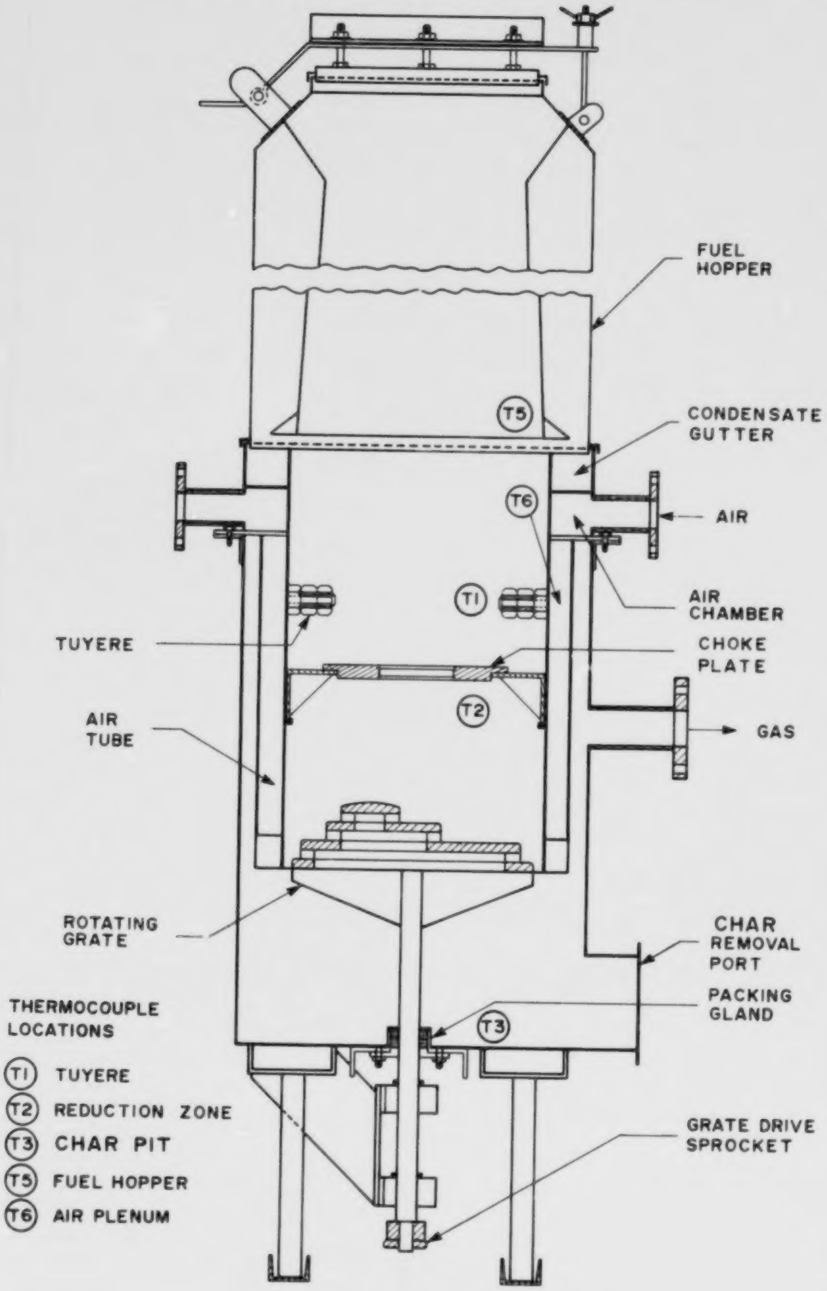

FUEL HOPPER
CONDENSATE GUTTER
T5
T6
AIR
AIR CHAMBER
T1
TUYERE
CHOKE PLATE
T2
AIR TUBE
GAS
ROTATING GRATE
CHAR REMOVAL PORT
PACKING GLAND
T3
THERMOCOUPLE LOCATIONS
T1 TUYERE
T2 REDUCTION ZONE
T3 CHAR PIT
T5 FUEL HOPPER
T6 AIR PLENUM
GRATE DRIVE SPROCKET

Figure 4. Cross-section - UCD sludge/wastepaper gasifier.

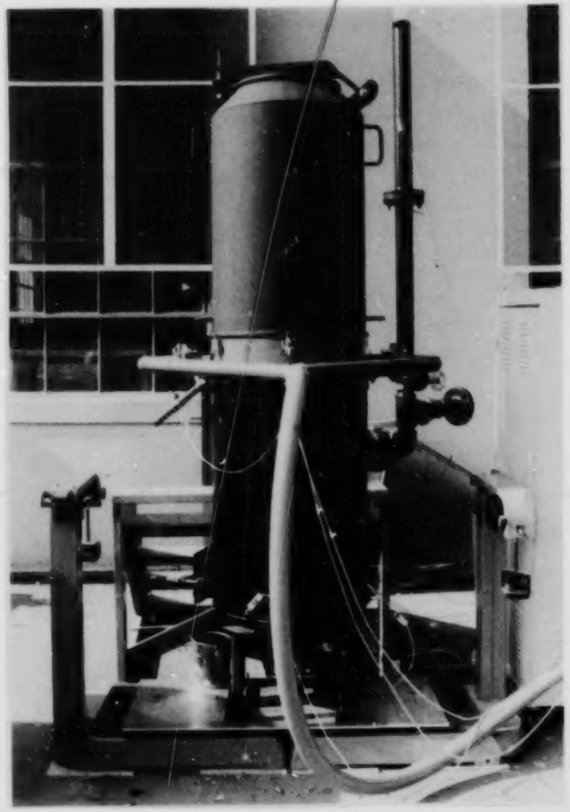


Figure 5. Exterior view - UCD sludge/wastepaper gasifier.

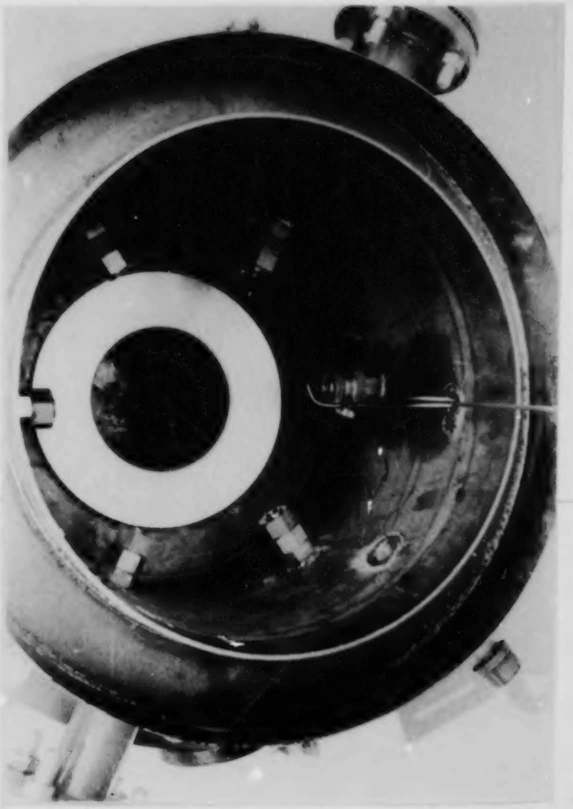


Figure 6. Interior view - UCD sludge/wastepaper gasifier.

The char pit is used to collect char during an experimental run. A rotating eccentric grate is located in the char pit immediately below the choke plate. The grate supports the fuel bed and allows passage of char and gas into the char pit. Gas is drawn off continuously through a pipe on the side of the char pit.

Gasifier Geometry - Little information is available in the literature concerning the geometric design of a gasifier. The only detailed work on the subject is contained in the report by Nordstrom (39). Between 1957 and 1963, his research group tried various designs and arrived at some empirical relationships between tuyere diameter, tuyere height relative to the venturi section, and venturi diameter relative to firebox diameter. Although these experiments were conducted on wood-fueled gasifiers, it was felt that Nordstrom's relationships could be used as a guide in the design of a gasifier for solid waste.

Curves presented by Nordstrom (39) were used to estimate the relative sizes of the choke plate orifice diameter, tuyere diameter, tuyere length, and distance between the tuyeres and choke plate. Because the tuyeres, choke plate, and choke support plate and hoop are removable, the internal geometry can be changed easily. A diagram showing the internal dimensions of the gasifier is shown in Figure 7 and Table 1.

Gasifier Construction - The choke plates and tuyeres were constructed from Type 304 stainless steel. A temperature resistant alloy, ASTM Type A515 was used for the firebox and the rotating grate. The remainder of the gasifier was constructed from Type 1040 mild steel.

Cyclone Design - A high efficiency cyclone was designed and constructed to remove particles greater than 10 microns from the producer gas stream. The design follows a Stairmand design (55) with a body diameter of 17.8 cm.

Data Acquisition

The data acquisition subsystem is an automated temperature measurement system. Type T, type K, and type R thermocouples are used to monitor temperatures of the inlet air, gasifier, and producer gas burner. Thermal emf from the thermocouples is converted to temperatures by a Digitec Model 1000 Datalogger. Channel number, temperature, and elapsed time are printed on the paper tape output of the instrument. To monitor three critical temperatures on a continuous basis three additional thermocouple readout devices were installed. These temperatures (voltages) were also recorded automatically by the datalogger. A photograph of the complete data analysis subsystem is shown in Figure 8.

Producer Gas Burner

A 1055 MJ/hr producer gas burner system was designed and constructed to provide a facility from which accurate gaseous and particulate analyses of the producer gas could be obtained. The producer gas burner system is shown in Figure 9. Important features of the producer gas burner system are:

1. Raw gas sampling pipe whose length is 10 pipe diameters (pipe diameter = 25.4 cm). A 10.2 cm diameter sample port is located eight pipe diameters downstream and two pipe diameters upstream of any flow

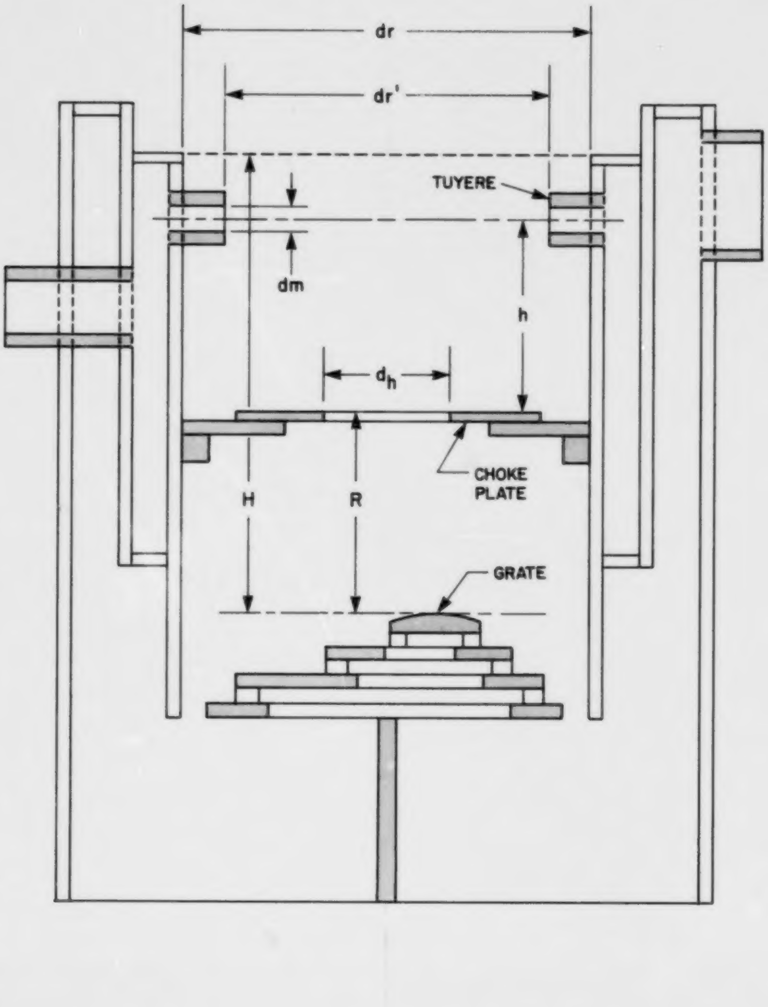

dr
dr'
TUYERE
dm
h
d_h
CHOKE PLATE
H
R
GRATE

Figure 7. Interior dimension symbols for a downdraft gasifier firebox.

16

Table 1

INTERNAL DIMENSIONS OF UCD CIVIL ENGINEERING SLUDGE/WASTEPAPER GASIFIER

Dimension	Symbol	Length (cm)
Firebox diameter	dr	45.7
Tuyere circle diameter	dr'	32.0
Tuyere diameter	dm	1.4, 1.7
Choke plate orifice diameter	dh	17.8
Tuyere - choke plate distance	h	11.4
Choke plate - grate distance	R	21.0
Overall firebox length	H	80.6

BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

8

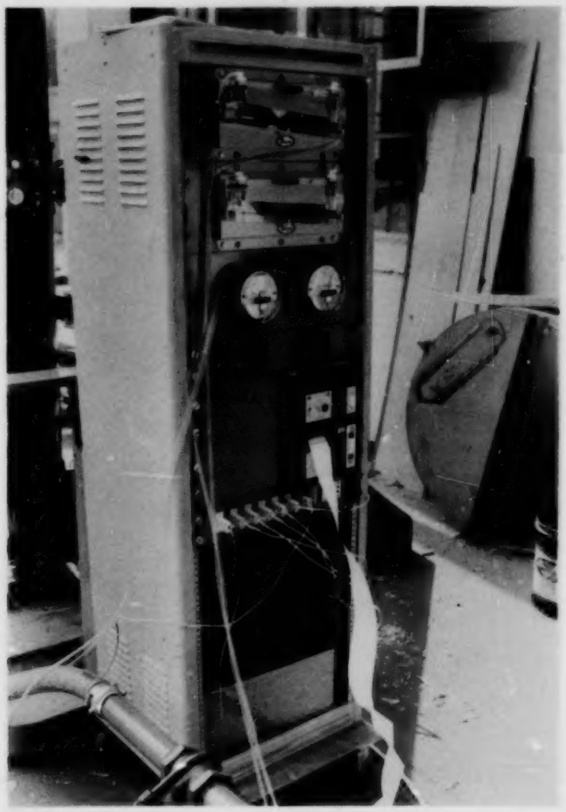
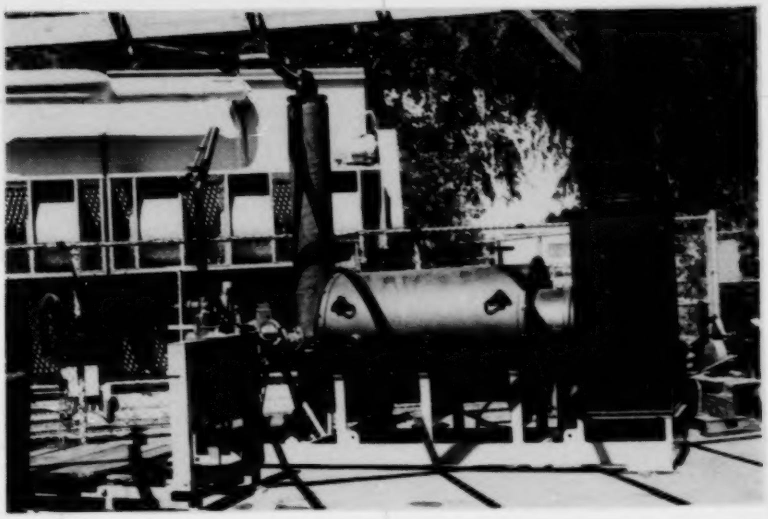


Figure 8. Data analysis subsystem for monitoring gasifier operation.

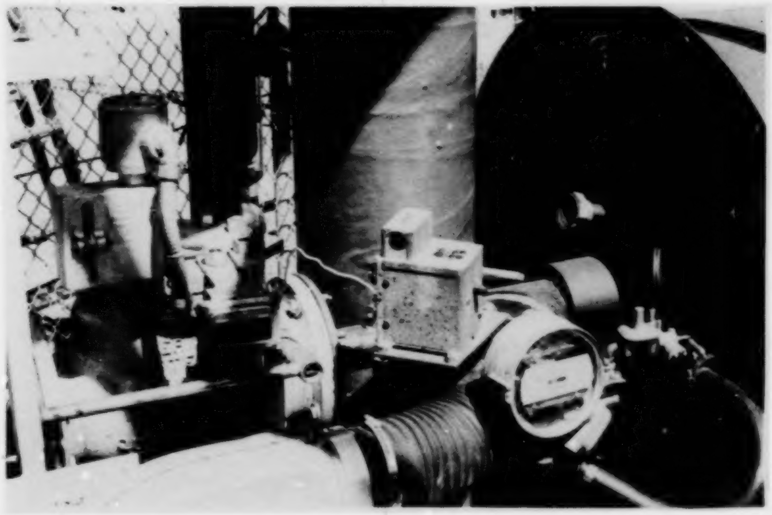
BEGIN LAST LINE OF TEXT
3/8"
BOTTOM OF IMAGE AREA; OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS

PAGE NUMBER
EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN. EPA FORM 347)
U.S. GOVERNMENT PRINTING OFFICE 1980-690-639
TYPING GUIDE SHEET

18



a. Overall view



b. Gas train and burner

Figure 9. Producer gas burner system.

EPA Form 2350-4 (4-80)
(PREVIOUSLY CIN: EPA FORM 237)
TYPING GUIDE SHEET

disturbance. With this design it is possible to make particle size measurements at typical gasification rates.

2. Producer gas burner and furnace was designed to provide a gas residence time of 1 second at 1093°C at a gasification rate of 90.7 kg/hr. Temperatures from thermocouples located at the producer gas inlet to the furnace, inside the furnace, and at the flue gas outlet are recorded continuously with a digital datalogger.

3. Flue gas stack whose length is 10 stack diameters (diameter = 45.7 cm). Two 10.2 cm diameter sample ports are located eight pipe diameters downstream and two pipe diameters upstream of any flow disturbance. The flue gas stack dimensions comply with EPA's particulate and velocity sampling criteria (57).

Solid Waste Shredding and Densification

Densified fuels are required for the operation of fixed bed gasifiers. The simplest type of densification system consists of a shredder followed by an agricultural type cubing machine. Originally built to produce densified alfalfa hay, these machines can be modified to produce solid waste fuel cubes.

Because the capacity of commercially available densification systems is relatively large (1.8 to 4.5 metric tons/hr) compared to the gasifier (16 to 100 kg/hr), a densification system was not built especially for this project. Rather, the pilot plant densification system operated by the Papakube Corporation, San Diego, California was utilized. Key features of the Papakube system include an integral shredder, a metering system which allows moistening the paper to the optimum moisture content, and a modified John Deere Cuber (see Figure 10). The extrusion dies of the machine have been modified with a proprietary coating and finishing treatment which is said to allow the densification of many materials without binding agents (37,38).

LABORATORY TESTING

Samples of gasifier fuels and char, were tested in the laboratory. The methods used are described in this section. The sampling techniques, apparatus, and methods used for fuel and char are summarized in Table 2. Proximate analyses of the fuel and char were run using a standard laboratory drying oven, muffle furnace, and analytical balance according to ASTM Standard Method (see Table 2). Ultimate analysis for percent C, H, N, S, and O of the fuel, char, and condensate was conducted by the Chemistry Department, University of California, Berkeley campus. The energy content of the fuel and char was determined with a Parr Oxygen Bomb Calorimeter.

FIELD TESTING

In addition to the gasifier temperatures that were recorded automatically by the data analysis subsystem, the following data were recorded manually during test runs.

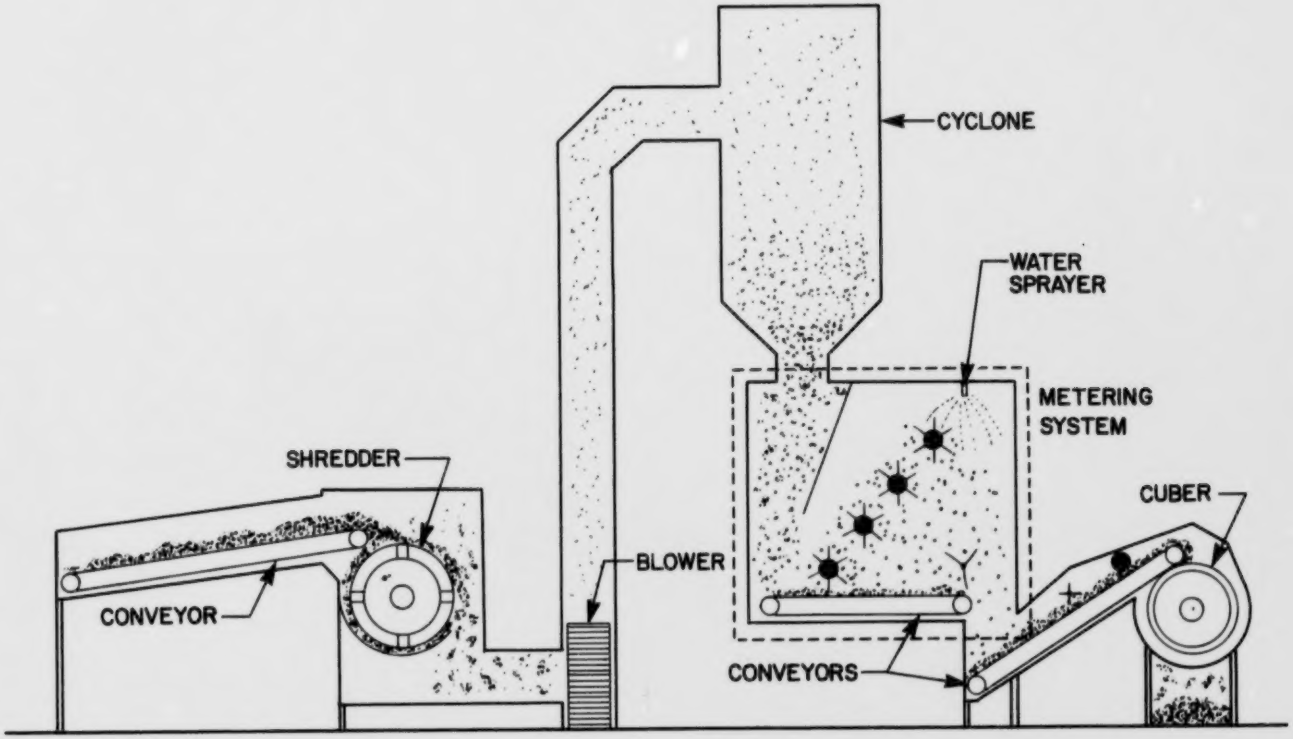

CYCLONE
WATER SPRAYER
METERING SYSTEM
SHREDDER
CUBER
BLOWER
CONVEYOR
CONVEYORS

Figure 10. Schematic diagram of the Papakube densification system.

Table 2

SUMMARY OF DATA COLLECTION AND ANALYSIS EQUIPMENT

Test	Sampling Technique	Apparatus	Reference
Proximate analysis	Grab samples of fuel and char	Drying oven, muffle furnace, desiccator	ASTM D3172-73 "Standard Method for the Proximate Analysis of Coke and Coal"
Ultimate analysis	Grab samples of fuel and char	C, H, N w/ Perkin-Elmer Gas Analyzer S by Grote Combustion Method ppt w/ $BaSO_4$	Micro-Analytical Laboratory Department of Chemistry University of California, Berkeley
Energy content	Grab samples of fuel and char	Parr Adiabatic Oxygen Bomb Calorimeter	ASTM D-2015-66 "Gross Calorific Value of a Solid Fuel by the Adiabatic Bomb Calorimeter
Cube physical properties	Grab samples of fuel	Laboratory balance	Reference 1

Air and Producer Gas Flows

Air flow was measured using standard flange mounted orifice plate in the air inlet line. The orifice plate was calibrated periodically using a portable venturi meter. The producer gas flowrate was usually determined by conducting a nitrogen balance on the gasifier assuming that the contribution of nitrogen in the fuel and char can be neglected. However the producer gas flowrate was measured directly for Runs 26, 27, 28-A, and 28-B using an EPA Reference Method 1 analysis. The direct measurement of the producer gas is discussed in Section 4.

Weight Loss

The entire gasifier is mounted on platform scales (see Figure 3). The weight of the gasifier was recorded at five minute intervals. Because only the producer gas leaves the reactor, the weight loss during the run is a direct measure of gas generation. The rate of gas generation is called the gasification rate.

Producer Gas Sampling and Analysis

The producer gas composition was monitored continuously using the sample train shown in Figures 11 and 12. The producer gas analyzer system is made up of four separate instruments: 1) Leeds and Northrup Model 7865 Multi-component infrared/thermal conductivity analyzer. The infrared analyzer was used for CO and CO_2 determinations while the thermal conductivity analyzer determined H_2, 2) Leeds and Northrup Model 7863 Thermomagnetic Oxygen Analyzer, and 3) Beckman Model 400 flame ionization hydrocarbon analyzer for CH_4. The percent by volume of dry producer gas at ambient temperature was determined for CO, CO_2, O_2, H_2, and total hydrocarbons while the percentage of N_2 was obtained by difference. A sample was continuously drawn from the producer gas stream at a point just downstream from the high efficiency cyclone. (Temperature measurements were also taken at this point, see Figure 3). Producer gas composition readings were taken every 5 minutes. The producer gas moisture content was determined using part of the Method 5 analysis once during each run.

Producer Drop

The pressure drop across the gasifier and the high efficiency cyclone were measured every 5 minutes.

Char

Char samples were collected on the day following the run to allow the gasifier to cool. Samples for analysis were collected from the char pit when the gasifier was partially disassembled for inspection after each run.

Condensate

At the conclusion of each run, condensate was drained from the gasifier and weighed.

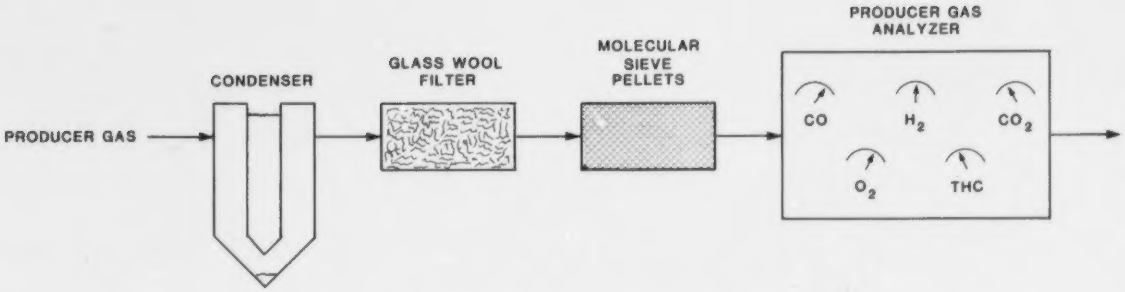

PRODUCER GAS
CONDENSER
GLASS WOOL FILTER
MOLECULAR SIEVE PELLETS
PRODUCER GAS ANALYZER
CO
H_2
CO_2
O_2
THC

Figure 11. Producer gas analysis system train.

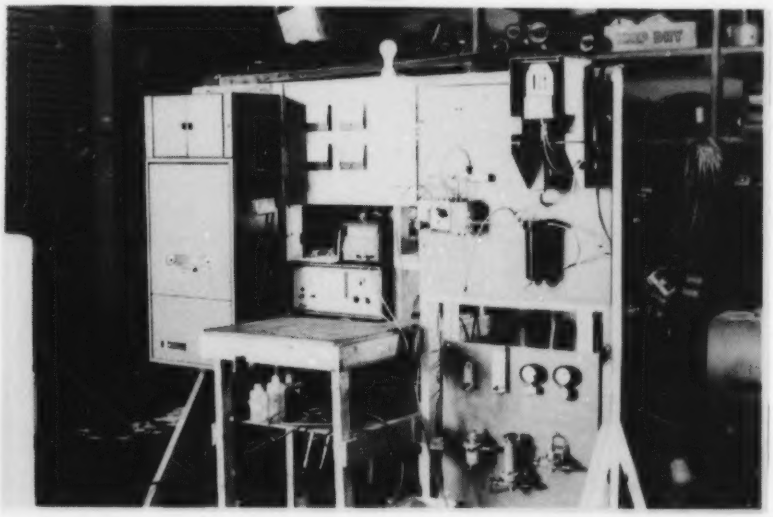


Figure 12. Producer gas analysis system.

Slag

To assess the potential of sludge/wastepaper cubes to cause slagging, the gasifier was partially disassembled after each run, and the residual char in the firebox removed and sifted for slag agglomerations. The quantity and location of the slag agglomerations were noted.

PREPARATION OF GASIFIER FUELS

The gasifier was fueled with three different types of fuels: sludge/wastepaper cubes, wastepaper cubes, and water hyacinth/wastepaper cubes. The fuels were prepared using the Papakube Densification System (see Figure 10). The preparation of these fuels is described below; the characteristics of the fuels are described in Section 4.

Densified Sludge/Wastepaper

Samples of lagoon dried, mixed primary and secondary sludge from the University wastewater treatment plant were collected and trucked to the Papakube plant in San Diego. Two batches of sludge/wastepaper mixtures at 20 percent sludge (by wet weight) were prepared by placing pre-weighed sludge and recycled newspaper on the conveyor of the system. The first batch of sludge/wastepaper cubes was made in July 1980 using lagoon dried sludge containing approximately 55 percent solids. The second batch of sludge/wastepaper cubes was made in March 1981 using lagoon dried sludge containing approximately 40 percent solids. About 900 kg of fuel cubes were made for batch 1 and about 3600 kg of fuel were made for batch 2.

It was assumed that the shredder and the blower of the Papakube system would provide adequate mixing of the sludge and wastepaper. To test this assumption, three samples were drawn randomly from the second batch of sludge/wastepaper cubes. Sixteen fuel cubes were drawn from the three samples and analyzed for ash content (on a dry basis) using the proximate analysis procedure discussed previously. The distribution of the percentage ash in the fuel cubes can be used to indicate the degree of mixing of the sludge and wastepaper, and thus the homogeniety of the sample if a) the percentage of ash and moisture in the wastepaper are constant, b) the percentage of ash and moisture of the sludge are constant and c) the percent ash in the wastepaper and the sludge is sufficiently different. Based on 16 fuel cubes it was found that the fuel cube ash content was distributed normally with a mean of 4.85 percent and a standard deviation of 1.91 percent. This represents a coefficient of variation of 39.4 percent which is relatively large for a "homogeneous" sample. Part of this variation may be due to inadequate mixing of the Papakube system. Another source of variation may be due to the fact that the sludge that was mixed with the wastepaper may not have had a uniform moisture content. Therefore it is not possible, at this time, to determine how well the Papakube system mixes sludge and wastepaper.

Densified Wastepaper

Recycled newspaper was purchased in San Diego and used for the densified wastepaper cubes. About 900 kg of wastepaper cubes were made.

Densified Water Hyacinth/Wastepaper

Water hyacinths harvested from the San Joaquin river, dried, and hand selected were trucked to the Papakube pilot plant in San Diego. In San Diego, recycled newspaper was purchased and used to make the water hyacinth/wastepaper cubes. A mixture of 25 percent (by weight) dried water hyacinth (moisture content = 6 percent) and 75 percent recycled newspaper (moisture content = 10 percent) was placed on the conveyer system shown in Figure 10. About 180 kg of water hyacinth/wastepaper cubes were made.

OPERATIONAL PROCEDURES

The standard operating protocol for each test run was as follows:

1. Weigh Empty Gasifier - The gasifier was weighed prior to fueling. Char from the previous run was left remaining in the gasifier up to the level of the tuyeres and partially combusted fuel was added up to the top of the firebox (see Figure 7) to aid in start up.

2. Fuel Gasifier - The fuel hopper was filled with fuel and the combined weight of the gasifier and fuel recorded.

3. Turn on Gasification Air - The blower bypass valve was set to supply to the desired flowrate as measured with the air inlet orifice. The flow was manually regulated during the run with the air bypass valve.

4. Ignite Gasifier Fuel - A steel rod was heated red hot with an acetylene torch and inserted into the gasifier ignition port. After smoke was emitted from the flare stack, the rod was removed and the port closed.

5. Ignite Gas - After the fuel was ignited, a propane torch was used to ignite the gas from the flare stack.

6. Record Data - The gasifier was weighed every 5 minutes, differential and static pressures were manually recorded, dry producer gas analysis data were taken, and temperatures automatically recorded with the Datalogger.

7. Grate Rotation - The rotating grate was operated to maintain a pressure drop across the gasifier of about 20 cm H_2O. Operation of the grate causes the displacement of char into the char pit and reduces pressure drop.

8. Producer Gas Moisture Content - After the gasifier reached steady state conditions, a sample of gas was drawn off and the gas moisture content was measured using an EPA Reference Method 5 procedure.

9. Refueling - After recording the data discribed in 6 above the inlet air was shut off. The fuel hopper lid was opened, fuel was added, the fuel hopper lid was closed, and the new weight was recorded. Then the char pit hatch was opened, the char was removed, and the weight was recorded. Finally, the high efficiency cyclone fly ash canister was removed, emptied and replaced,

and the weight was recorded. The refueling procedure took between 5 and 15 minutes.

10. Shut Down - The blower was turned off and the blower valve was closed tc prevent backflow into the blower.

11. Condensate Removal - Condensate from the fuel hopper gutter was drained and weighed.

Post Experimental Run

On the day following the completion of each run the standardized procedure outlined below was followed.

1. Unload Char - The gasifier was weighed, the char was removed from the char pit and the gasifier was reweighed.

2. Gasifier Teardown - With the char pit empty the gasifier was weighed. The fuel hopper was removed and the gasifier was reweighed. Any fuel remaining above the top of the firebox (see Figure 7) was removed and weighed. Then fuel and/or char was removed and weights recorded at the following levels in the gasifier firebox: tuyeres, choke plate, grate. Char samples were taken and all slag was removed, weighed, and retained for later analysis. Char that was removed from the char pit was also checked for small slag agglomerations. The char was then reloaded into the gasifier up to the level of the tuyeres and partially combusted fuel was added up to the top of the firebox.

MASS AND ENERGY BALANCE COMPUTATIONS

To aid in the analysis of the gasification process, mass and energy balances on the gasifier runs were calculated. A complete discussion of the method of computation is found in Appendix A.

SECTION 4

EXPERIMENTAL RESULTS

The experimental phase of this project consisted of a series of fourteen gasifier runs fueled with three types of densified fuel and operated at various rates. The gasifier run summaries, operational data, and energy balances are presented in this section.

GASIFIER RUN SUMMARIES

There are four goals in the experimental phase of this project: to determine the effect of air input rate on various gasification parameters, to operate the gasifier so that air pollution data could be gathered, to evaluate the performance of a small diesel engine operating on producer gas, and to determine the feasibility of gasifying aquatic plants used in the treatment of wastewater.

To evaluate the effect of the air input rate on various gasification parameters gasifier Runs 17, 18, 19, 20, 21-A, and 21-B were completed. Each of these gasifier runs was operated with one fuel consisting of a densified mixture of 20 percent sludge and 80 percent recycled newspaper.

Gasifier Runs 26, 27, 28-A, and 28-B were conducted primarily to provide air pollution data. Because the fuel used for these runs was also a densified mixture of 20 percent sludge and 80 percent recycled newspaper the operational data were also used to evaluate the effect of the air input rate various gasification parameters.

The performance of a small scale diesel engine using producer gas was evaluated during Runs 14, 15, and 16. These tests were conducted in cooperation with the Department of Agricultural Engineering at UCD. The fuel used for these tests was densified recycled newspaper. To evaluate the feasibility of gasifying aquatic plants with wastepaper, Run 13 was conducted.

OPERATING DATA

The operational data obtained from the gasifier runs is contained in this section. A discussion of fuel characteristics, char characteristics, and an operation summary is discussed below.

Fuel Characteristics

To quantify the physical and chemical properties, the gasifier fuels were tested for moisture content, energy content, bulk density, ultimate analysis, and proximate analysis. A description of the methods used for the tests is found in Table 2 and a summary of the results is found in Table 3. The use of the proximate analysis test was discontinued after Run 19 because the ultimate analysis data provided a more detailed characterization of the fuel.

In general, the gasifier fuels tested were relatively high in volatile combustible matter (VCM), low in carbon content, and low in energy content (HHV) as compared to coal. The bulk densities of the sludge/wastepaper fuels were significantly higher than the bulk densities of the wastepaper fuels. The higher density of the sludge/wastepaper can be attributed to the presence of the sludge, which acts as a binding agent. Representatives from the Papakube Corporation suggested that bulk densities of 560 kg/m^3 could easily be attained if desired (41).

Char Characteristics

A summary of the chemical properties of the char for each gasifier run are found in Table 4. A description of the methods of analysis used to determine the char properties is found in Table 2. The proximate analysis test was discontinued after Run 19 because the ultimate analysis data provided a more detailed characterization of the sample.

Because char is the major waste product of the gasification process it is desirable to minimize its production. The char represents an energy loss as well as a waste product that must be disposed. From Table 4, it is clear that a major fraction of the char consists of carbon.

It can be noted from Table 4 that the percentage of carbon in the char for Runs 26, 27, 28-A, and 28-B is significantly lower than the percentage of carbon for the other runs using similar fuels. This phenomenon can be explained by analyzing the factors which control the chemistry of the reduction process in the gasifier. A reduction of the carbon content of the char can be encouraged by the production of CO. The following reactions are the major means by which solid carbon can be converted to CO:

$$CO_2 + C = CO - 172{,}600 \text{ KJ/kg.mole}$$

$$H_2O + C = CO + H_2 - 131{,}400 \text{ KJ/kg.mole}$$

Both of these reactions are highly endothermic requiring high temperatures (>700°C) and long residence times to reach equilibrium.

The residence time of a piece of char in the gasifier is controlled by: a) the air input rate, b) the length of the reduction zone (distance R in Figure 7), c) the speed of grate rotation, and d) the size of the grate openings. The length of reduction zone and the size of the grate openings remained constant throughout all the gasifier runs tested during this period. Both the air inlet rates and the grate

Table 3

FUEL SUMMARY

Run #	Fuel Type	Moisture Content (% by wet weight)	Energy Content (Dry Basis, HHV) (MJ/kg)	Bulk Density (Kg/m^3)	Ultimate Analysis (% by weight)						Proximate Analysis (% by weight)			
					C	H	O	N	S	Residue	MC	VCM	FC	Ash
13	water hyacinth/ wastepaper	9.9	16.61	488	NA	NA	NA	NA	NA	NA	8.5	69.0	16.0	6.5
14	wastepaper	9.4	19.42	399	47.19	5.96	45.72	0.04	0.09	1.0	6.3	80.8	12.0	0.9
15	wastepaper	8.8	19.42^a	399^a	47.19^a	5.96^a	45.77^a	0.04^a	0.09^a	1.0^a	6.3^a	80.8^a	12.0^a	0.09^a
16	wastepaper	9.4	19.42^a	410	47.19^a	5.96^a	45.72^a	0.04^a	0.9^a	1.0^a	6.3^a	80.8^a	12.0^a	0.9^a
17	20% sludge/ wastepaper	10.1	18.73	499	45.02	5.62	44.14	0.34	0.08	4.8	6.6	74.3	15.4	3.7
18	20% sludge/ wastepaper	11.4	18.87	510	45.29	5.72	43.84	0.35	0.20	4.6	6.2	75.4	15.3	3.1
19	20% sludge/ wastepaper	11.4^b	18.79	499	45.39	5.79	43.90	0.31	0.11	4.3	6.6	75.7	13.0	4.7
20	20% sludge/ wastepaper	6.1	18.82	NA	45.59^c	5.79^c	43.90^c	0.31^c	0.11^c	4.3^c	NA	NA	NA	NA
21-A,21-B	20% sludge/ wastepaper	6.2	18.93	NA	45.39^c	5.79^c	43.90^c	0.31^c	0.11^c	4.3^c	NA	NA	NA	NA
22-A,22-B	wastepaper	7.3	NA	379	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
26	20% sludge/ wastepaper	9.6	18.54	NA	46.02	5.86	43.12	0.46	0.04	4.5	NA	NA	NA	4.9^d
27,28-A,28-B	20% sludge/ wastepaper	9.6^e	18.54^e	NA	46.02^e	5.86^e	43.12^e	0.46^e	0.04^e	4.5^e	NA	NA	NA	4.9^e

NA - Not available, MC = Moisture content, VCM = Volatile combustible matter, FC = Fixed carbon

[a] Value not available, value from Run 14 assumed

[b] Value not available, value from Run 18 assumed

[c] Value not available, value from Run 19 assumed

[d] Mean value based on 16 cubes, dry basis

[e] Value not available, value from Run 26 assumed

Table 4

CHAR SUMMARY

Run #	Fuel Type	Energy Content (Dry Basis, HHV) (MJ/Kg)	Ultimate Analysis (% by weight)						Proximate Analysis (% by weight)			
			C	H	O	N	S	Residue	MC	VCM	FC	Ash
13	water hyacinth/ wastepaper	20.84	NA	NA	NA	NA	NA	NA	1.2	2.8	53.5	42.5
14	wastepaper	25.31	70.93	0.59	2.78	0.18	0.02	25.5	0.3	5.4	70.8	23.5
15	wastepaper	26.19	73.29	0.69	2.69	0.19	0.04	23.1	0.2	4.4	74.7	20.7
16	wastepaper	30.44	86.62	0.92	2.64	0.09	0.03	9.7	0.6	4.0	84.0	11.4
17	20% sludge/ wastepaper	24.62	70.53	0.51	1.06	0.18	0.12	27.6	0.3	2.9	71.0	25.8
18	20% sludge/ wastepaper	25.50	71.97	0.76	0.94	0.25	0.08	26.0	0.7	3.2	71.6	24.5
19	20% sludge/ wastepaper	26.20	76.27	0.65	1.52	0.27	0.09	21.2	0.6	3.3	74.1	22.0
20	20% sludge/ wastepaper	21.82	62.98	0.27	1.70	0.13	0.02	34.9	NA	NA	NA	NA
21-A	20% sludge/ wastepaper	25.69	68.71	1.59	6.79	0.36	0.05	22.5	NA	NA	NA	NA
21-B	20% sludge/ wastepaper	26.60	73.46	2.59	9.70	0.53	0.12	13.6	NA	NA	NA	NA
26	20% sludge/ wastepaper	15.88	50.68	0.40	0.0	0.18	0.01	49.3[a]	NA	NA	NA	NA
27	20% sludge/ wastepaper	17.73	51.98	0.30	0.34	0.17	0.01	47.2	NA	NA	NA	NA
28-A,28-B	20% sludge/ wastepaper	15.62	48.18	0.30	0.0	0.20	0.01	51.4[a]	NA	NA	NA	NA

NA - Not available, MC = Moisture content, VCM = Volatile combustible matter, FC = Fixed carbon

[a] As oxides, therefore total is greater than 100%

rotation speed from Runs 26, 27, 28-A, and 28-B were higher than those of the other runs. The higher air inlet rates and grate rotation speeds for Runs 26, 27, 28-A, and 28-B imply a shorter residence time. Thus the variation of the carbon contents of the chars cannot be explained by a residence time argument.

It can be concluded from Table 5 that the gas outlet temperatures for Runs 26, 27, 28-A, and 28-B are significantly higher than those of the other runs. These higher temperatures are attributed to the addition of insulation of the outside of the gasifier firebox which was done prior to the start of Run 26.

Thus, with the present configuration, only the temperature seems to control the carbon content of the char. However, if the length of the reduction zone (length R in Figure 7) was increased, both the carbon content of the char and the exit temperature should be lowered. An extended reduction zone could reduce both the loss of carbon in the char and specific heat of the gas. Both of these factors would yield an improved gasifier efficiency.

Another method that could be employed to utilize more fully the carbon in the char would be to blend it in with the fuel on subsequent runs. However because of the high ash content of the char and the stringent limitations on gasifier fuel ash content, blending of char and fuel does not seem feasible. However, char may be used as a substitute for powered activated carbon used in the polishing of wastewater. The feasibility of char as a substitute for activated carbon is discussed in Section 5.

Operational Summary

An operational summary of each gasifier run conducted for this project is presented in Table 5. The gasification rate is defined as the weight loss during the run divided by the net run time and represents the mass rate of producer gas production. Because the entire gasifier system was mounted on a platform scale the gasification rate was determined directly from the scale readings. The fuel consumption rate, often cited in gasification literature, is defined to be the sum of the gasification rate, char production rate, condensate production rate, fly ash collection rate, and the slag generation rate.

Condensate and Slag Production

A brief description of the condensate and slag production that occurs in the gasification process follows.

Condensate - Condensate collected in the gasifier is produced by condensing vapors formed in the fuel hopper. These vapors are condensed between the double walls of the fuel hopper and collected in the condensate gutter (see Figure 4). Because of its negligible influence on the gasification process a chemical analysis of the condensate was not performed for this project. However an ultimate analysis for condensate samples collected from previous gasifier runs is found in Reference 60.

In the gasification experiments conducted with agricultural wastes, Jenkins (26) found that condensate is about 80 percent water and that the average energy content was 4.75 MJ/kg. He also observed that the condensate collected in the

Table 5
OPERATIONAL SUMMARY

Item	RUN 13	RUN 14	RUN 15	RUN 16	RUN 17	RUN 18	RUN 19	RUN 20	RUN 21-A
Fuel description	water hyacinth/ wastepaper	wastepaper	wastewater	wastepaper	20% sludge	20% sludge	20% sludge	20% sludge	20% sludge
Gasification rate, Kg/hr	15.2	29.6	35.4	37.9	20.6	31.9	27.7	33.2	30.1
Char production rate, Kg/hr	2.5	3.6	4.5	4.5	1.6	3.1	3.1	3.1	3.5[c]
Condensate production rate, Kg/hr	0.8	0.0	0.0	0.4	0.4	0.2	0.5	0.1	0.4[c]
Fly ash collection rate, Kg/hr	-	-	-	-	-	-	-	.09	.10[c]
Slag generated, Kg	2.7	0.1	0.8	0.0	0.4	0.1	0.2	0.1	0.0
Air input rate, m^3/min (20°C, 1 atm)	0.45	0.56	0.67	0.71	0.48	0.63	0.76	0.82	0.71
Gas output rate, m^3/min (20°C, 1 atm)	N/A	1.06	1.20	1.34	0.86	1.12[b]	1.37[b]	1.44	1.27
Average reduction zone temperature, °C	715	901	960	911	882	907	966	972	954
Average gas outlet temperature, °C	158	247	229	249	249	325	327	439	434
Net run time, min	220	150[a]	30[a]	115[a]	312	274	286	252	230

[a] Represented only part of total run

[b] Assuming a gas moisture content of 10%

[c] Averaged over all of Run 21

[d] An estimate, exact value not obtained

[e] Assuming the same dry gas composition as Run 28-B

[f] Averaged over all of Run 28

Table 5 (continued)

Item	RUN 21-B	RUN 22-A	RUN 22-B	RUN 23-D	RUN 25	RUN 26	RUN 27	RUN 28-A	RUN 28-B
Fuel description	20% sludge	wastepaper	wastepaper	wastepaper	20% sludge	20% sludge	20% sludge	20% sludge	20% sludge
Gasification rate, Kg/hr	37.1	51.0	87.0	100.7	75.0	68.3	69.0	74.4	70.6
Char production rate, Kg/hr	3.5[c]	3.7	7.4[d]	N/A	6.6	9.1	8.1	8.0	6.6
Condensate production rate, Kg/hr	0.4[c]	0.0	0.0	N/A	N/A	0.4	0.1	0.0	0.0
Fly ash collection rate, Kg/hr	0.1[c]	N/A	N/A	N/A	N/A	1.6	0.5	0.5	0.5
Slag generated, Kg	0.0	0.0	0.0	None	N/A	0.05	0.19	0.01[f]	0.19[f]
Air input rate, m^3/min (20°C, 1 atm)	0.82	1.15	1.92	1.99	1.88	1.87	1.86	2.09	1.89
Gas output rate, m^3/min (20°C, 1 atm)	1.49	2.19	3.61	3.61[b]	N/A	3.62[b,e]	3.56[b,e]	4.22	3.93
Average reduction zone temperature, °C	1027	892	977	962	1052	1060	1057	1039	1037
Average gas outlet temperature, °C	554	407	550	512	654	658	672	630	595
Net run time, min	77	95	55	27[b]	90	155	303	150	299

[a] Represents only part of total run

[b] Assuming a gas moisture content of 10%

[c] Averaged over all of Run 21

[d] An estimate, exact value not obtained

[e] Assuming the same dry gas composition as Run 28-B

[f] Averaged over all of Run 28

condensate gutter was produced primarily during start-up and shut-down. For that reason, the condensate gutter and the double-walled fuel hopper are not necessary for gasifier that will be operated on a continuous basis.

Slag - The fuel ash content plays an important role in the downdraft gasification process. In addition to lowering the energy content of the fuel, the presence of ash in the fuel encourages the formation of slag in the gasifier. Rambush (43) stated that the minerals in the fuel ash form an eutectic mixture of lowest melting point. If the temperature inside the gasifier firebox is greater than the temperature of lowest melting point, the mixture will melt. In the downdraft gasifier the molten ash flows together and moves downward into the cooler parts of the gasifier where it forms slag or clinkers that cling to the internal surfaces, tuyeres, and grate. The formation of clinkers on the choke plate and grate can block the flow of char through the gasifier causing an increase in the air/fuel ratio and temperature. With the increase in the air/fuel ratio, the producer gas becomes of such poor quality that it cannot be combusted. If the air/fuel ratio reaches the stoichiometric value, the temperature can become very high, and melting of the gasifier firebox can occur, causing severe damage.

The slagging potential of a fuel is not only a function of the gasifier temperature and the percentage of ash, but also a function of the composition of ash. To get an idea of the slagging potential of sludge/wastepaper fuels, an elemental analysis was performed. The results of an elemental analysis performed on the fuel, char, flyash, and sludge using the PIXE (particle induced x-ray emission) system at the Crocker Nuclear Laboratory on the UCD campus are reported in Appendix C. From Table 6 it is clear that a large fraction of the inorganic matter is composed of the elements Si, Ca, Fe, Ti, and K. If the fuel composition shown in Table 6 is modified to consist of only the elements Si, Ca, and Fe, and these elements are converted to their oxides, the temperature at which slagging occurs could be estimated with the appropriate phase diagram. Because the oxidation state of iron in the fuel is not known, there are two phase diagrams which could be used to describe to the fuel ash; a CaO-Fe_2O_3-SiO_2 system or a CaO-FeO-SiO_2 system. If a CaO-Fe_2O_3-SiO_2 system is used to describe the fuel ash the mass distribution of elemental oxides would be the following: $CaO = 24.6\%$, $Fe_2O_3 = 34.1\%$, $SiO_2 = 41.3\%$. Using a CaO-Fe_2O_3-SiO_2 phase diagram shown in Figure 13a and the mass distribution of elemental oxides, shown on Figure 13a by a ▲, the melting temperature of the fuel ash can be estimated to be 1250°C. If a CaO-FeO-SiO_2 system is used to describe the fuel ash the mass distribution of elemental oxides would be the following: $CaO = 25.5\%$, $FeO = 31.7\%$, $SiO_2 = 42.8\%$. Using a CaO-FeO-SiO_2 phase diagram shown in Figure 13b and the mass distribution of elemental oxides, shown on Figure 13b by a ■. The melting temperature of the fuel ash can be estimated to be about 1225°C. If there are elemental oxides other than calcium, iron, and silicone oxides present in the fuel ash, the fuel ash melting temperatures determined above will be affected and these melting temperatures can only be interpreted as estimates. Because temperatures of 1250°C or greater can be obtained in a downdraft gasifier (between the tuyeres and the choke plate), the potential for the formation of slag exists in sludge/wastepaper gasification systems.

Several techniques can be used to control slagging. The easiest solution is to limit the ash content of the sludge/wastepaper cubes by controlling the ratio of sludge to wastepaper. Another method involves the injection of steam or CO_2 in

Table 6

ANALYSIS OF METALS IN 20 PERCENT SLUDGE/WASTEPAPER FUEL AND CHAR

Element	Percent total metals found	
	Fuel[a]	Char
Na	1.9	—
Al	2.0	5.9
Si	24.9	27.0
P	—	1.4
S	1.3	—
Cl	0.9	—
K	3.8	3.9
Ca	22.7	21.6
Ti	5.6	5.5
V	0.7	0.4
Cr	1.5	1.1
Mn	0.9	0.9
Fe	30.7	30.7
Ni	0.2	0.1
Cu	0.8	1.0
Zn	1.6	0.4

[a] Average values from four samples

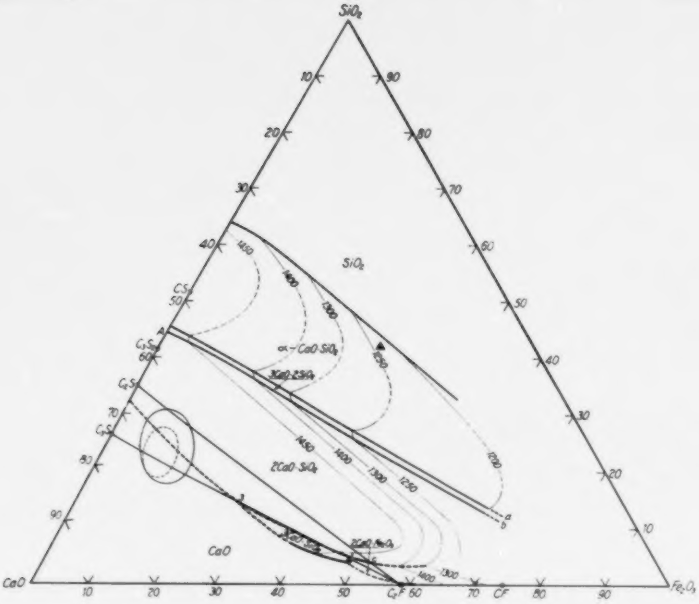

SiO₂
10
20
30
40
CS
50
A
C₃S₂
60
C₂S
70
C₃S
80
90
CaO
10
20
30
40
50
C₂F
60
70
CF
80
90
Fe₂O₃
90
80
70
60
50
40
30
20
10
SiO₂
1450
1400
1300
1250
α-CaO·SiO₂
3CaO·2SiO₂
1450
1400
1300
1250
1200
2CaO·SiO₂
3CaO·SiO₂
2CaO·Fe₂O₃
CaO
1400
1300
a
b

Figure 13a. Phase diagram for a CaO-Fe_2O_3-SiO_2 system (7).

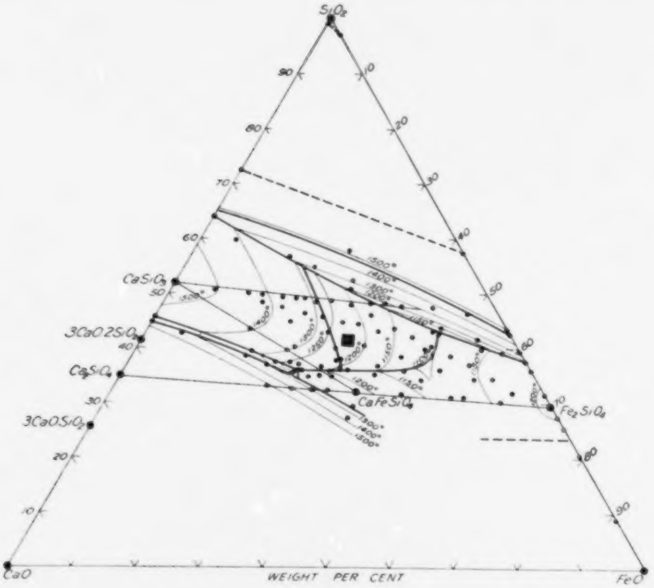

SiO₂
90
80
70
60
CaSiO₃
50
3CaO2SiO₂
40
Ca₂SiO₄
30
3CaOSiO₂
20
10
CaO
WEIGHT PER CENT
FeO
10
20
30
40
50
60
70
Fe₂SiO₄
80
90
1500°
1400°
1300°
1200°
1150°
CaFeSiO₄
1300°
1400°
1500°

Figure 13b. Phase diagram for a CaO-FeO-SiO_2 system (6).

the air blast causing a reduced gasifier temperature. Jenkins (26) had some success in controlling the build-up of slag by operating the grate continuously.

In addition to causing problems inside the gasifier by encouraging slag formations, certain substances can be vaporized, leave the gasifier in the gas stream, and then condense, forming very small particles. Although the silicon oxides have a fairly high melting point (2230°C), it has been shown that considerable amounts of SiO_2 can be formed as extremely small (0.1 micron), highly abrasive particles. These particles are very difficult to remove from the gas stream and can cause wear on machinery downstream of the gasifier (engines, gas turbines, etc) (30).

The mineral content in the fuel is recognized to have a catalytic effect on the gasification reactions and can increase the reactivity of the fuel. Additional information about catalytic biomass gasification can be found in References 18 and 50.

Producer Gas Analysis

Producer gas analysis data were taken for all gasifier runs except Runs 13, 26, and 27. (Producer gas composition data were taken for Runs 26 and 27 but were discarded due to a leak in the gas analysis system.) The producer gas analysis system was discussed previously and is shown in Figures 11 and 12.

Average values of the dry producer gas composition, moisture content, and energy content are reported in Table 7. The average values of the dry producer gas composition were obtained by averaging gas values taken when the gasifier reached a "steady state" condition. The term "steady state" for this gasifier is defined to occur when the reduction zone temperature is greater than 800°C and no gasifier shutdown (for refueling or other minor repairs) has occurred for 10 minutes. Because of limitations on the amount of fuel in the fuel hopper and the capacity of the char pit, a "true" steady state condition has never been realized. However with an enlarged fuel hopper and a continuous char removal mechanism a "true" steady state condition can be approached. A profile of the variations of the gas composition, energy content, reduction zone temperature, and gas outlet temperature throughout Run 28-A are shown in Figure 14. The breaks that occur in the profile indicate that the gasifier was shut down for refueling. Note that the shape of the producer gas energy profile is influenced greatly by the fraction of total hydrocarbons in the producer gas. Thus the shape of energy content profile indicates clearly the importance of the total hydrocarbon fraction on the overall gas content.

MASS AND ENERGY BALANCES

Mass and energy balances for Runs 14, 15, 16, 17, 18, 19, 20, 21-A, 21-B, 26, 27, 28-A, and 28-B were calculated using the computer program described in Appendix A. Listings of the program and printouts for each run are found in Appendix B.

A summary of the mass and energy balances for these runs is presented in Table 8. As mentioned previously, producer gas analysis data for Runs 26 and 27 are not available. Because of the similarity of operating parameters for Runs 26, 27, 28-B, it was assumed that the dry producer gas composition for Runs 26 and 27

Table 7

COMPOSITION AND ENERGY CONTENT OF PRODUCER GAS

Item	RUN 13	RUN 14	RUN 15	RUN 16	RUN 17	RUN 18	RUN 19	RUN 20	RUN 21-A
Dry gas composition By volume)									
CO, %	N/A	21.5	23.3	21.5	22.1	22.7	23.2	22.1	23.5
H_2, %	N/A	16.1	16.0	15.5	14.6	15.2	15.2	15.2	15.3
CH_4^a, %	N/A	3.29	0.95	2.52	1.62	1.12	1.43	1.30	1.05
$C_2H_4^a$, %	N/A	1.41	0.41	1.08	0.70	0.48	0.61	0.56	0.45
CO_2, %	N/A	11.6	10.3	12.0	11.2	10.9	10.4	10.6	10.4
N_2^b, %	N/A	46.1	48.9	47.4	49.9	49.6	49.2	50.2	49.3
Gas moisture content (By volume), %	14.6	N/A	N/A	N/A	10.9	N/A	N/A	10.5	10.4
Gas energy content, MJ/m^3 (Dry gas, LHV, 25°C, 1 atm)	N/A	6.02	4.89	5.52	4.99	4.84	5.07	4.87	4.90

[a] Measured as total hydrocarbons, CH_4 assumed to be 70% of THC, C_2H_4 assumed to be 30% of THC

[b] N_2 includes nitrogen, argon, and trace amounts of nitrogen oxides. N_2 is determined by difference, $N_2 = 100\% - (CO + H_2 + THC + CO_2 + O_2)$

[c] Dry gas analysis not available, values assumed equal to those of Run 28-B

Table 7 (continued)

Item	Run 21-B	RUN 22-A	RUN 22-B	RUN 23-D	RUN 26[c]	RUN 27[c]	RUN 28-A	RUN 28-B
Dry gas composition (By volume)								
CO, %	23.0	24.2	22.3	20.0	22.5	22.5	23.8	22.5
H_2, %	15.5	16.6	16.4	16.0	16.4	16.4	16.4	16.4
CH_4^a, %	1.54	1.68	2.10	2.38	1.82	1.82	1.82	1.82
$C_2H_4^a$, %	0.66	0.72	0.90	1.02	0.78	0.78	0.78	0.78
CO_2, %	10.8	10.5	11.6	12.3	11.5	11.5	11.2	11.5
N_2^b, %	48.5	46.3	46.7	48.3	47.0	47.0	46.0	47.0
Gas moisture content (By volume), %	10.4	N/A	N/A	N/A	12.6	12.5	14.7	15.3
Gas energy content, MJ/m^3 (Dry gas, LHV, 25°C, 1 atm)	5.14	5.38	5.37	5.22	5.33	5.33	5.49	5.33

[a] Measured as total hydrocarbons, CH_4 assumed to be 70% of THC, C_2H_4 assumed to be 30% of THC

[b] N_2 includes nitrogen, argon, and trace amounts of nitrogen oxides. N_2 is determined by difference, $N_2 = 100\% - (CO + H_2 + THC + CO_2 + O_2)$

[c] Dry gas analysis not available, values assumed equal to those of Run 28-B

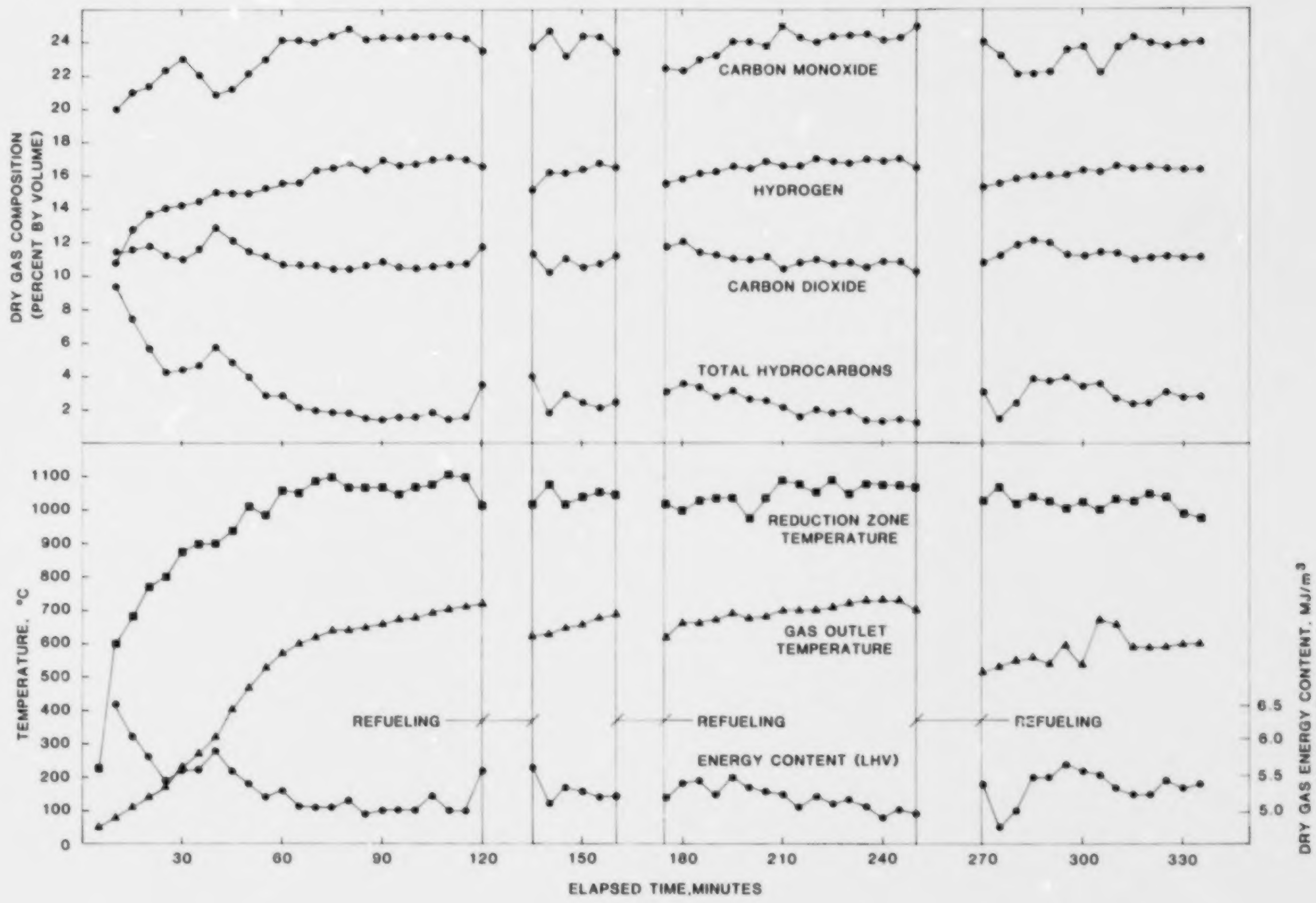


Figure 14. Producer gas composition and temperature profile for Run 28-A.

Table 8
MASS AND ENERGY BALANCES FOR GASIFIER RUNS 14 THROUGH 28-B

Run number	14	15	16	17	18	19	20	21-A	21-B	26	26 adj	27	27 adj	28-A	28-A adj	28-B	28-B adj
Mass Balance																	
Air rate, kg/hr	40.44	48.38	51.27	34.66	45.49	54.88	59.21	51.27	59.21	135.04	145.87	134.32	143.70	150.93	154.54	136.48	153.09
Wet fuel rate, kg/hr	33.20	39.90	42.80	22.70	35.20	31.30	36.50	34.10	41.10	79.40	105.83	77.70	101.10	82.90	111.96	77.70	146.32
Dry gas rate, kg/hr	60.68	68.61	75.75	49.12	64.42	78.02	82.59	72.76	85.26	199.41	215.40	198.34	212.20	227.27	232.70	201.54	226.06
Gas moisture rate, kg/hr	8.07	13.71	12.50	5.89	11.45	7.16	9.04	9.35	10.61	14.49	27.00	13.69	24.82	12.14	27.76	13.20	48.30
Char rate, kg/hr	3.60	4.50	4.50	1.60	3.10	3.10	3.20	3.50	3.50	9.10	12.02	8.10	10.54	8.00	10.80	6.60	12.42
Fly ash rate, kg/hr	—	—	—	—	—	—	0.10	0.10	0.10	1.60	2.11	0.50	0.65	0.50	0.68	0.50	0.95
Excess mass, kg/hr	1.29	1.46	1.32	0.75	1.73	-2.10	0.89	-0.34	0.85	-10.15	-4.84	-8.61	-3.40	-14.08	-5.45	-7.65	-11.68
Energy Balance																	
Energy in char, percent	15.77	16.83	18.39	10.43	13.66	15.86	10.56	14.91	12.81	10.98	10.88	11.15	11.15	9.10	9.09	8.01	8.00
Energy in fly ash, percent	—	—	—	—	--	—	0.31	0.43	0.37	1.93	1.91	0.69	0.69	0.57	0.57	0.61	0.61
Sensible energy in gas, percent	5.24	5.79	5.69	6.08	7.80	8.01	9.40	9.25	11.17	14.96	13.94	15.39	14.37	14.75	13.44	13.63	11.79
Chemical energy in gas, percent	64.68	48.55	56.63	64.57	53.85	77.54	62.90	59.30	60.73	82.11	66.54	83.45	68.62	92.20	69.90	84.80	50.51
Energy losses, percent	14.31	28.84	19.29	18.92	24.69	-1.41	16.82	16.11	14.92	-9.98	6.73	-10.68	5.17	-16.61	6.69	-7.04	29.09
Hot gas efficiency, percent	65.27	51.16	58.35	66.40	58.14	80.51	68.13	64.76	67.88	91.41	75.89	93.08	78.26	100.75	78.65	92.58	58.81
Cold gas efficiency, percent	60.03	45.37	52.67	60.32	50.35	72.49	58.73	55.51	56.72	76.44	61.95	77.70	63.89	86.00	65.20	78.95	43.03

was the same as the dry producer gas composition for Run 28-B. Therefore the energy balances for Runs 26 and 27 were computed using the dry producer gas analysis data from Run 28-B.

The energy balances calculated initially for Runs 26, 27, 28-A, and 28-B yielded results that were clearly impossible. For example the percent energy loss (including radiation losses) which is calculated by difference, for Runs 26, 27, 28-A, and 28-B was calculated to be -9.98, -10.68, -16.61, and -7.04 percent respectively. Energy losses for Runs 14 through 21-B ranged from -1.41 to 28.84 percent (average of 16.94 percent) while Kjellstrom (31) reported that heat loss due to radiation ranged from 6.5 to 15 percent. Despite the fact that insulation was added to the firebox prior between Run 21-B and Run 26, it can be deduced from the negative energy losses found above that something is in error.

To determine the source or sources of error in the energy balance computations, it is necessary to look at the input data to the mass balance. The input parameters that may be in error in the calculation of the mass balance are fuel, char, gas output, and air input rates. In the absence of direct measurement, the gas outlet rate is determined by calculating a nitrogen balance on the gasifier using the air input rate and the assumption that the fuel and char make negligible contributions of nitrogen. A nitrogen balance was calculated to determine the gas output rate for Run 28-A by taking into account the nitrogen in the fuel and char. The value obtained by considering the nitrogen in the fuel and char was found to differ from the value obtained by neglecting the nitrogen in the fuel and char by less than .04 percent. Because air pollution stack tests were conducted during Runs 26, 27, 28-A, and 28-B the gas output rate was measured directly as part of the EPA Reference Method 5 test. (For complete details, see Section 5.) The air input rate is determined by monitoring the pressure drop across an orifice plate and comparing the pressure drop with a previously calibrated value. The fuel, char, and condensate rates are determined by scale readings. (Due to its negligible contribution to the overall energy balance, the condensate energy is contained in the energy losses term). Because all of the parameters of concern (air input rate, gas output rate, fuel and char rates) are measured, two parameters may be used to calculate the third. A significant difference between the calculated and measured values might indicate the source of error.

The first comparison between measured and calculated values involves using the air input rate, the fuel input rate dry producer gas data (calibrated with standards before each run), and the producer gas moisture content, to calculate the gas output rate using a nitrogen balance. This was the method used initially to compute energy balances for Runs 26, 27, 28-A, and 28-B. This method was also used to compute energy balances for Runs 14 to 21-B. As previously noted this method yields impossible results for Runs 26, 27, 28-A, and 28-B (negative energy losses).

The second comparison between measured and calculated values is found by performing a carbon balance to find the gas output rate by using the fuel, char, and condensate rates and the producer gas composition. The air input rate is then calculated by using the previously calculated gas outlet rate and a nitrogen balance. The results of this comparison imply that the air input rate and the gas outlet rate are wrong.

The third comparison involves the determination of the fuel char rates from the gas output data. To make this comparison, it is necessary to assume that the ratio of the fuel consumed to the char produced, experimentally determined from the gasifier run, is correct. The char and fuel rates are obtained by calculating a carbon balance using the producer gas output rate, the producer gas composition, and the ratio of the fuel consumed to the char produced. The air input rate is determined by a nitrogen balance.

The results of this comparison yield: a) cold gas efficiencies of 61.95, 63.89, 65.20 and 48.03 percent (which are typical), b) energy losses of 6.73, 5.17, 6.69, and 29.09 percent, c) air input rates within 8.0, 7.0, 2.4, and 12.2 percent of the measured values, d) fuel and char rates of 33.3, 30.1, 35.1, and 88.3 percent greater than the measured values, for Runs 26, 27, 28-A, and 28-B, respectively.

With the exception of the adjusted values obtained from Run 28-B, the latter comparison seems to yield the most believable results. Therefore it will be assumed that systematic errors in the scale readings were the cause for the erroneous results cited previously. Given the physical location of the gasifier during Runs 26, 27, 28-A, and 28-B a series of systematic scale reading errors is possible. However because the exact nature of the errors is not understood, the mass and energy balances results for Runs 26, 27, 28-A and 28-B are reported in Table 8 in two ways.

First, the mass and energy balance data based on measured air input rate, fuel input rate, and dry producer gas data are reported in Table 8 as Run 26, 27, 28-A, and 28-B. Then, mass and energy balance data based on the adjusted fuel and char rates (calculated by performing a carbon balance on the experimentally determined fuel to char rate ratio, the producer gas composition, and the producer gas output rate) are reported in Table 8 as 26 adj, 27 adj, 28-A adj, and 28-B adj.

Referring to Table 8, mass balances for each run are reported in units of kg/hr while the units for the energy balance are reported as percentages of the input fuel energy, expressed as higher heating values (HHV). The most significant parameter in the mass balance is excess mass term, which represents the particulate matter not collected in the cyclone, the tar vapor in the producer gas, and any other mass that is not measured. Negative values of the excess mass term indicate inaccuracies in the mass balance input data. The chemical energy in gas is the most significant energy output, ranging from 48.55 to 77.54 percent of the input energy. The gas sensible heat for Runs 14 to 21-B ranged from 5.24 to 11.17 percent of the input net energy. With the addition of insulation before the start of Run 26 the sensible heat of the gas increased for Runs 26, 27, 28-A, and 28-B and ranged from 11.79 to 15.39 percent. The most significant energy output is the char and fly ash energy, which ranges from 8.61 to 18.39 percent of the net input energy. As discussed earlier the char generation rate is a function of residence time in the gasifier, the internal dimensions of the gasifier, and the temperature inside the gasifier. With the proper design and operation of the gasifier the char generation rate could be minimized.

The cold gas efficiency is expressed as the lower heating value (LHV) of the chemical energy in the gas divided by the input fuel energy (expressed as a HHV). The hot gas efficiency is the sum of the cold gas efficiency and the percent sensible energy in the gas. The cold gas efficiencies ranged from 43.03 to 72.49 percent of the fuel input energy while the hot gas efficiencies ranged between 51.16 and 80.51 percent. The hot gas efficiency represents the conversion efficiency that can be expected if the gasifier is used with in a boiler application (the sensible energy of the producer gas can be used). For engine and gas turbine applications the cold gas energy efficiency represents the expected conversion efficiency.

SECTION 5

DISCUSSION

The experimental results described in Section 4 are discussed in this section in four parts dealing with: evaluation of gasifier performance, air pollution emissions test, feasibility of using gasifier char as a source of activated carbon, and operation of a small diesel engine with producer gas.

EVALUATION OF GASIFIER PERFORMANCE

Evaluation of the performance of the gasifier, based on the results from Runs 13 to 28-B, is presented in three parts dealing with operating parameters, quality of producer gas, and gasifier design.

Operating Parameters

Operating parameters that affect the performance of the gasifier significantly are air input and gasification rates, internal gasifier temperatures, slag formation, turn-down ratio, and fuel flow characteristics.

Air Input and Gasification Rate - The air input rate is the most easily controlled operating parameter in the gasification process. In the absence of changes in the fuel composition and gasifier dimensions, the air input rate affects directly the gasification rate and the gasifier reaction zone temperature and indirectly affects the producer gas composition. Thus, an understanding of the relationship between the air input rate and the gasification rate is important in evaluating the performance of the gasifier.

The specific gasification rate is an operational parameter used to compare gasifiers of different size. The specific gasification rate is defined to be the gas output rate expressed in mass or volume terms divided by a characteristic gasifier area. There are numerous definitions of the specific gasification rate including: gasification rate in kg/hr divided by the area of the firebox, gasification rate in kg/hr divided by the tuyere circle area (defined by the area of the circle inscribed by the tuyeres), gasification rate in kg/hr divided by the area of the choke plate opening, and the gasification rate in Nm^3/hr divided by the choke plate opening area. Kaupp et al. (30) reported that an upper limit of 1 Nm^3 of producer gas per hour per square centimeter of choke plate area has been established for small portable downdraft gasifiers. The highest specific gasification rate obtained was 0.95 $Nm^3/hr \cdot cm^2$ (during Run 28-A) which is close to the maximum reported by Kaupp.

It is advantageous to operate the gasifier at a high specific gasification rate. The most obvious advantage is that the cost of the gasifier is minimized if operated close to its maximum gas output. A gasifier operated at a high specific gasification rate will maintain a high reactor temperature which is necessary to maintain a producer gas of good quality.

The maximum specific gasification rate (MSGR) can be determined theoretically by knowing the chemical composition of the fuel. The MSGR for wood occurs at an equivalence ratio of 0.225 (44). The equivalence ratio (ER) is defined as the oxidant to fuel weight ratio divided by the stoichiometric ratio. Because there are many factors that influence the gasification rate, theoretical determinations of the MSGR are at best a good initial estimate of the actual MSGR.

The actual MSGR can be determined by observing several changes that occur in the gasification process. As more air is added to the gasifier, the reaction zone expands. The MSGR corresponds to the gasification rate at which the reaction zone no longer expands. Further addition of air will push the gasification reactions towards combustion reactions, causing increases in the CO_2 concentration and gas temperature, and decreases in the CO and total hydrocarbon (THC) concentration. This change influences the air/fuel ratio, fuel consumption rate, gas composition and gas temperature.

Changes in the producer gas composition with various air input rates can be seen in Figure 15. Because the THC fraction is present in all gasifier runs and that the CO_2 and CO fraction have remained relatively constant, it can be concluded that the MSGR has not been reached. Thus to reach the MSGR it is necessary to increase the air input rate until a consistent increase in the percentage of CO_2 in the producer gas is obtained.

Internal Gasifier Temperatures - As discussed previously, the temperatures reached in the reaction zone of the gasifier influence greatly all aspects of the gasifier performance. With the pilot scale gasifier used in this project, the temperature which best represents the reaction zone temperature is designated the reduction zone temperature. The location of the thermocouple used to measure the reduction zone temperature is shown in Figure 4. The variation of the reduction zone temperature during a gasifier run can be seen in Figure 14. As shown in Figure 14, once the gasifier is "up-to-temperature", the reduction zone temperature remains relatively constant.

High internal gasifier temperatures influence the gasification process in many ways: 1) tars, higher hydrocarbons and other products of fuel distillation in the gasifier are thermally cracked to non-condensible hydrocarbons in the hot partial combustion zone of the gasifier, 2) the chemical equilibrium for the formation of CO and H_2 is favored by high temperatures, 3) the tendency for the formation of slag is affected greatly by the internal gasifier temperature.

Slag Formation - One of the most important results obtained from this study is that the gasification of sludge/wastepaper fuels is possible without disruptive slag formation. This result is very important because the formation of slag is one of the most critical problems in the operation of downdraft gasifiers. Because the disposal of sludge (which has an ash content of 25-30 percent, dry basis) is the major goal of this project, the ability to gasify fuels with an ash content of at least 5 percent is critical to the economic feasibility of sludge/wastepaper gasification in small communities. Based on the data summarized in Table 5, the gasification of

48

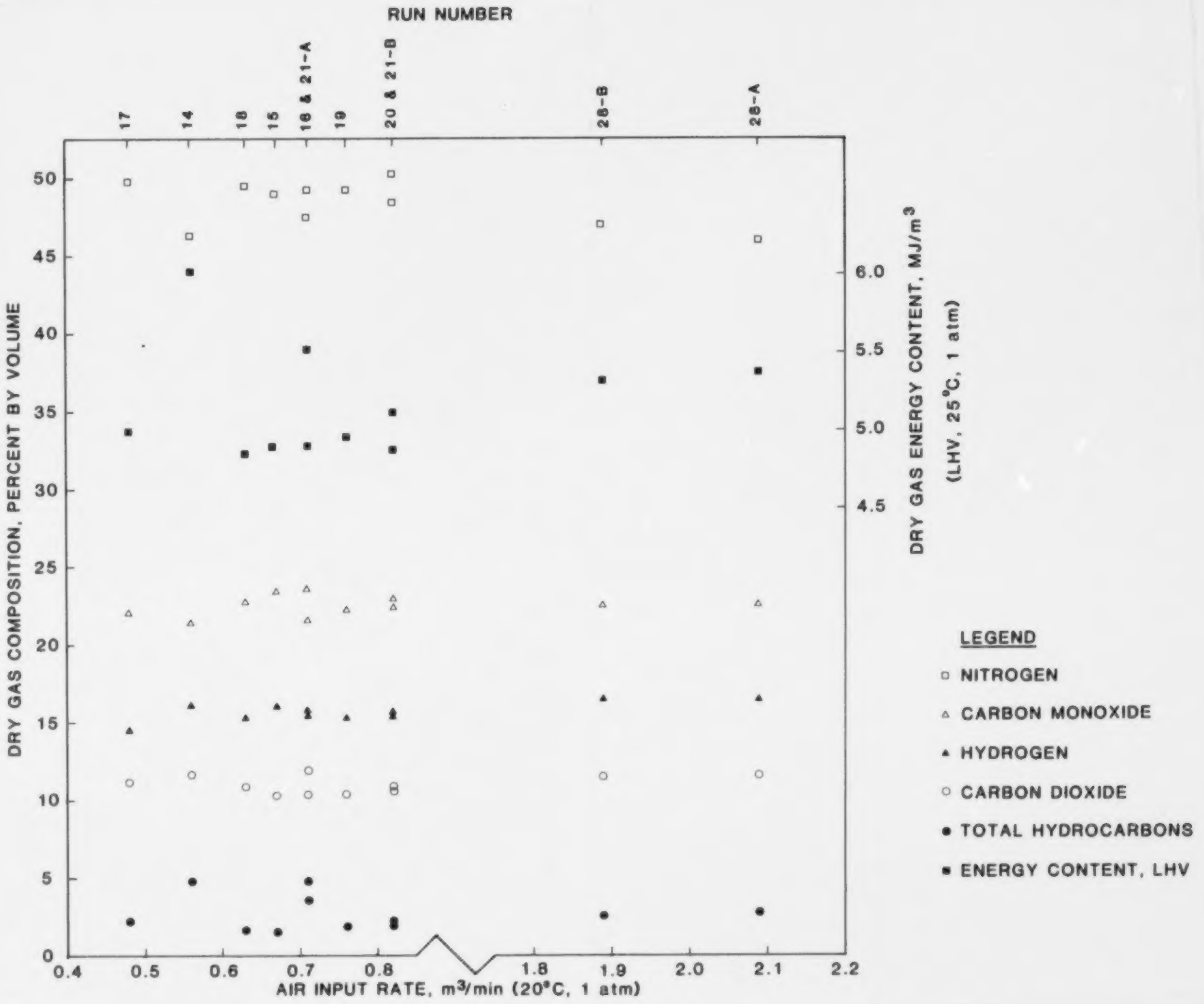


Figure 15. Producer gas composition vs. air input rate.

20 percent sludge/wastepaper and wastepaper fuels can be accomplished without significant slag formation.

The only gasifier run in which significant slag formation occurred was during Run 13. The fuel used in Run 13 was a mixture of 25 percent dried water hyacinths which were grown in a river and 75 percent recycled wastepaper. As noted in Table 5, 2.7 kg of slag were removed from the gasifier at the conclusion of Run 13. Not only was the slag generated during Run 13 excessive (compared with quantities collected in other runs) but the bulk of the 2.7 kg was made up of one large piece of slag. The large piece of slag was found directly over the chokeplate, effectively blocking the flow of char through the gasifier. Had an effort to continue Run 13 been attempted, meltdown of the gasifier might have occurred.

The high degree of slag formation observed in Run 13 is due to high ash content of the water hyacinths used in the fuel. The water hyacinths used for this test were harvested from a river (San Joaquin in California) with a very high silt content. Therefore based on the results of Run 13, it was concluded that the gasification of water hyacinths grown in water of high silt content is not feasible. Because of these findings, further tests with river grown water hyacinths were not considered.

Small quantities of water hyacinths grown in primary effluent from a wastewater treatment plant were analyzed in the laboratory. It was found that water hyacinths grown in primary effluent had an ash content of 16.1 percent (dry basis) while water hyacinths used for Run 13 had on ash content of 34.8 percent (dry basis). While the gasification of water hyacinths grown in silt laden river water may not be feasible, the gasification of water hyacinths grown in wastewater may be feasible.

Because the previously gasifier work done (Reference 61) also dealt with the gasification of sludge/wastepaper mixtures it is important to compare the quantities of slag generated during the runs described in this report with the runs documented in Reference 61. In reviewing the data from Runs 9, 10, 11, 12 of the previous gasifier work, it was found that the sludge/wastepaper fuels tested had ash contents of 1.2, 2.9, 3.4 and 4.5 percent (dry basis) respectively. The slag collected from Runs 9, 10, 11, 12 was 0.6, 1.2, 0.8, and 1.0 kg. From Table 5 it is clear that the quantity of slag collected during Runs 9, 10, 11, 12 was significantly greater than the quantity of slag collected during Runs 17, 18, 19, 20, 21, 26, 27, 28 ($\leq$ .4 kg). Because the fuel ash contents from Runs 17, 18, 19, 20, 21, 26, 27, 28 (see Table 3) are generally greater than the fuel ash contents from Runs 9, 10, 11, 12, the correlation between fuel ash content and slag generated does not seem to hold. To explain why the quantity of slag generated in Runs 9, 10, 11, 12 is greater than the quantity of slag generated during Runs 17-21, 26-28, it is necessary to analyze the differences in operational parameters between the two sets of runs.

The major difference in operational parameters between Runs 9-12 and Runs 17-21, 26-28 is that the latter set of runs were operated at much higher air input rates and higher grate speed rotation. Because the air input rate and the speed of grate rotation determine the residence time of the fuel in the gasifier, these parameters may be used to control slag formations in the gasification of high ash fuels. Jenkins (26) came to a similar conclusion in his work with the gasification of agricultural wastes. Further work needs to be done to support and quantify these conclusions.

Because an increase in the speed of grate rotation increases the char energy losses, a trade-off may exist between high gasifier efficiency and slag free operation. If the operation of the gasifier at a high grate speed permits the gasification of fuels with a large sludge to wastepaper ratio, the decrease in gasifier efficiency is not significant. The effect of sludge to wastepaper ratios on the economics of sludge/wastepaper gasification is discussed in Section 6.

Turn-down ratio - Based on chemical energy output of the producer gas, it was found that a turndown ratio of nearly 5 to 1 was experienced for sludge/wastepaper fuels. Large turndown ratios, common in downdraft gasifiers, could be important if the gasifier must provide varying quantities of gas in a boiler application. However, large turn-down ratios cannot be applied to gasifiers used to fuel engines or gas turbines. At low gasification rates, the tar vapor content of the producer gas increases so that the gas is unsuitable for engine or gas turbine use.

Fuel flow characteristics - A problem commonly experienced in working with downdraft gasifiers is the inability of the fuel to flow through the gasifier. Because the fuel must flow through the gasifier by gravity and without mechanical assistance, the ability of the fuel to flow through the gasifier is very important to the trouble free operation of the gasifier. To eliminate blockages, or "bridges" in the fuel bed, downdraft gasifiers require a dense, uniformly sized fuel. Densified mixtures of sludge and wastepaper all had excellent flow properties and caused no problems with regards to bridging.

Quality of Producer Gas

Although the primary purpose of this project is the disposal of sludge and wastepaper in an economic and environmentally acceptable manner, the production of energy from this process is critical to economic feasibility of sludge/wastepaper gasification. Thus the quality and stability of the gas produced are important variables in assessing the success of the project.

The most important application of producer gas is in its conversion to mechanical energy using an internal combustion engine or a gas turbine. Producer gas that is to be used in engines and turbines must 1) have a relatively steady gas composition that is sufficient to sustain combustion, 2) have a low temperature, 3) have a minimum amount of tars, and 4) be free of particulate matter. Because the particulate matter in the producer gas is determined primarily by the clean-up equipment used rather than the operation of the gasifier, particulate matter in the producer gas is not discussed here.

As shown in Figure 15, the producer gas composition remained relatively constant over a wide range of air input rates. The energy content of the producer gas was adequate in all cases for use in an engine. Test results from the use of a dual-fuel diesel engine fueled with producer gas are presented at the end of this chapter.

The three gaseous constitutents that make up the combustible fraction of the producer gas are CO, H_2, and total hydrocarbons (THC). Based on producer gas analyses from the gasification of sludge/wastepaper fuels, the THC fraction was found to contain about 70 percent CH_4 and about 30 percent C_2H_4. The major combustible fraction of the producer gas is made up of CO and H_2. The following chemical equations can be used to describe the formation of CO and H_2 in the gasifier:

(Boudouard reaction) $C + CO_2 = 2CO - 172,600$ kJ/kg•mole

(water gas reaction) $C + H_2O = CO + H_2 - 131,400$ kJ/kg•mole

(water shift reaction) $CO + H_2O = CO_2 + H_2 + 41,200$ kJ/kg•mole

Because both the Boudouard reaction and the water gas reaction are strongly endothermic, the production of large amounts of CO and H_2 occurs at high gasifier temperatures. The correlation between high gasifier temperatures and high concentrations of CO and H_2 in the producer gas is supported by the data reported in Figure 14.

Because the energy content of CH_4 and C_2H_4 are much greater than the energy contents of CO and H_2, small changes in the THC fraction of the producer gas influence greatly the overall energy content of the producer gas. This phenomenon is illustrated in Figures 14 and 15. From Figure 15 it can be concluded that the gasifier runs with the highest energy contents occurred when the THC fraction was significant. In analyzing the producer gas composition changes throughout Run 28-A (see Figure 14) the peaks in the energy content curve correspond to the peaks in the THC curve. Therefore to produce a producer gas of high energy content it is important to encourge THC formation in the gasifier.

The formation of CH_4 can occur by two different chemical mechanisms in the gasifier. The first mechanism for CH_4 production occurs in the distillation zone where gases (including CO_2, CO, CH_4, C_nH_{2n}), tars, pyroligneous acids, light and heavy oils, and water vapor are produced. Though the production of CH_4 and other non-combustible hydrocarbons resulting from the distillation process is desired, the presence of tar vapor that accompany these gases creates many problems in a gasifier system. If tar laden producer gas is used in an engine or gas turbine, valves and other internal parts will become gummed quickly. Therefore tar vapor in the producer gas cannot be tolerated when used to fuel engines or gas turbines.

A gasifier that requires extensive tar removal is unacceptable for two reasons. First, the extraction of tar vapor is difficult and expensive. Second, the tar has the highest heating value of all combustible products obtained from the gasification of organic matter (30). It is therefore desirable to thermally crack the tars into non-condensible hydrocarbons and other products. Thermal cracking of tars is accomplished to a large degree in a properly designed downdraft gasifier operated at high temperatures.

The second mechanism by which CH_4 is produced in a gasifier is via a weakly exothermic reaction:

$$C + 2H_2 = CH_4 + 75,000 \text{ KJ/kg•mole}$$

As shown in Figure 16, the production of CH_4 is favored by low temperatures. Thus a trade-off between high CH_4 production and low producer gas tar content exists. Because of the problems associated with tar vapor removal a producer gas with a low tar content is prefered for small installations.

As mentioned previously, the producer gas must be cooled when used to fuel engines and gas turbines. The fraction of producer gas sensible heat for each gasifier run is shown graphically in Figure 17. Note that the sensible heat fractions for Runs 26, 27, 28-A and 28-B are much higher than for previous runs. This increase is due primarily to the addition of insulation and the higher air input rates. Therefore the producer gas sensible heat fractions represent a system loss. Any utilization of this waste heat would increase the overall efficienty of the gasifier system.

One of the most useful ways to use the sensible heat of the producer gas is to encourge the formation of CO via the Bouduoard reaction. The importance of high temperatures for the production of CO is illustrated in Figure 18. Because the Boudouard reaction is highly endothermic, the formation of CO will, in effect, cool the gasifier and thus the producer gas. Though temperature measurements of the producer gas as it exits the reduction zone (near the bottom of the grate, see Figure 7), were not taken, it is estimated that the producer gas has sufficient sensible heat to permit the increased production of CO via the Boudouard reaction.

An extended reduction zone (length R in Figure 7) may increase the CO concentration in the gas, resulting in a decrease in the char carbon content. However if the reduction zone length is increased so that the gas temperature falls below 500°C, the gas composition can "freeze," causing heavy soot formation via the reaction $2CO \rightarrow C + CO_2$. Therefore, there seems to be an optimum reduction zone length which will maximize CO production and minimize gas sensible heat losses. Jenkins (26) recommended that experimental work be conducted to quantify the optimum reduction zone length.

Thus, a high quality producer gas can be obtained if the gasifier is operated at the high temperatures necessary to crack tar vapors, and if the gasifier has a reduction zone of sufficient length to maximize CO production. Based on qualative measurements taken during Runs 26 and 27, the producer gas had a very low tar content. It is the goal of future work to determine the optimum reduction zone length as a function of the fuel, air input rate, and internal gasifier dimensions.

Gasifier Design

Design factors that influence the operation and performance of the gasifier are discussed in this section. A hypothetical design of a full size sludge/wastepaper gasification system is also considered.

Internal Gasifier Dimensions - As discussed earlier, the most important criteria for the design of a gasifier used to fuel on engine or gas turbine is the ability to produce a gas of sufficient energy content and low tar content. Based on the experimental results from this research, the gasifier used in this project seems to fulfill these criteria. However, it is impossible to conclude at this time that the internal gasifier dimensions utilized in this project are optimum for the fuel used. Because of the large number of variables influencing all aspects of the gasification process, optimum internal gasifier dimensions must be determined experimentally.

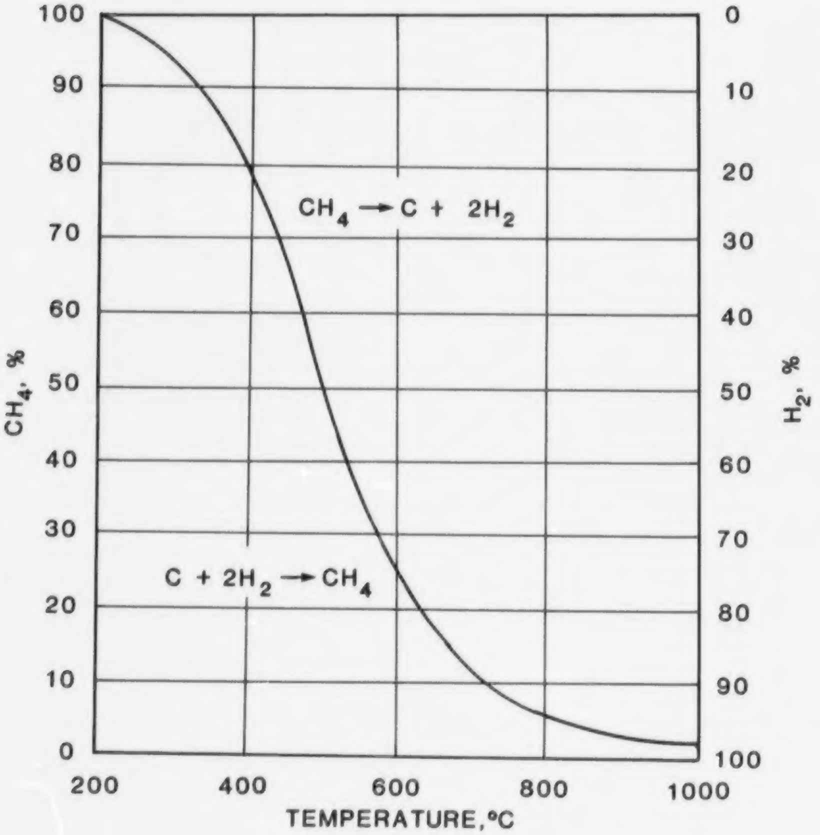


Figure 16. Equilibrium curve for methane at 1 atmosphere pressure (19).

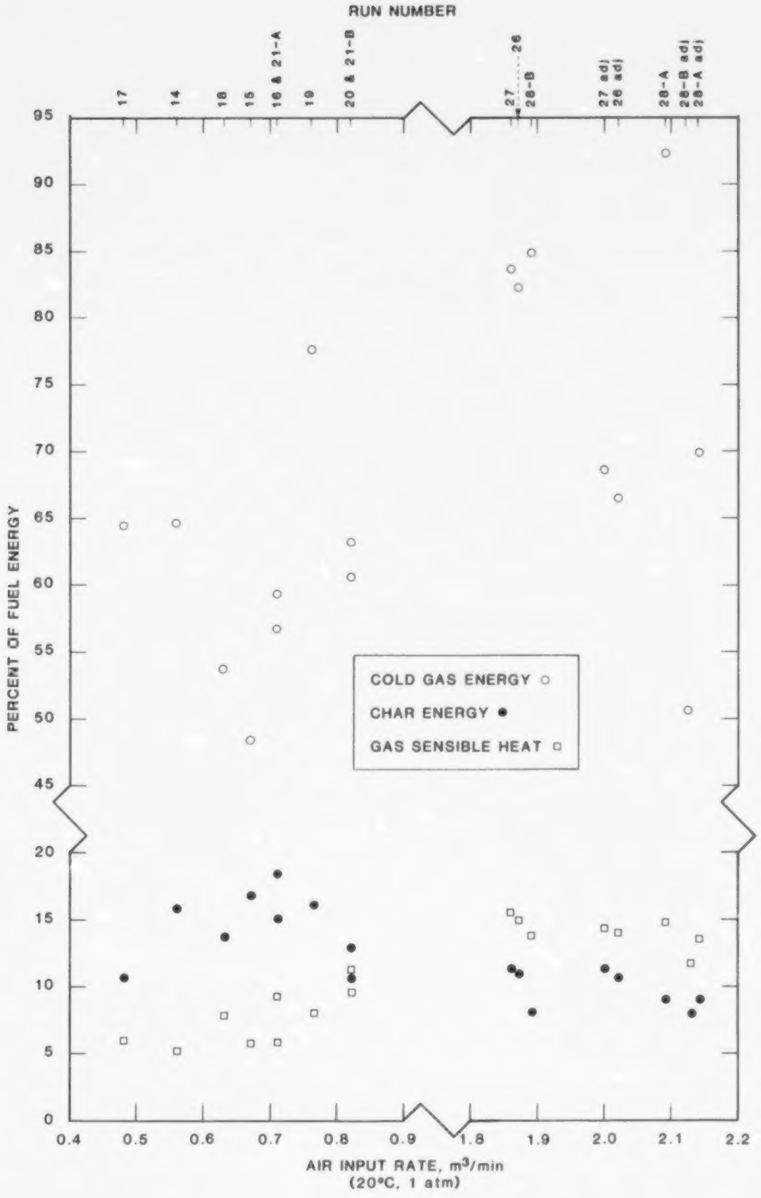


Figure 17. Gasifier efficiencies vs. air input rate.

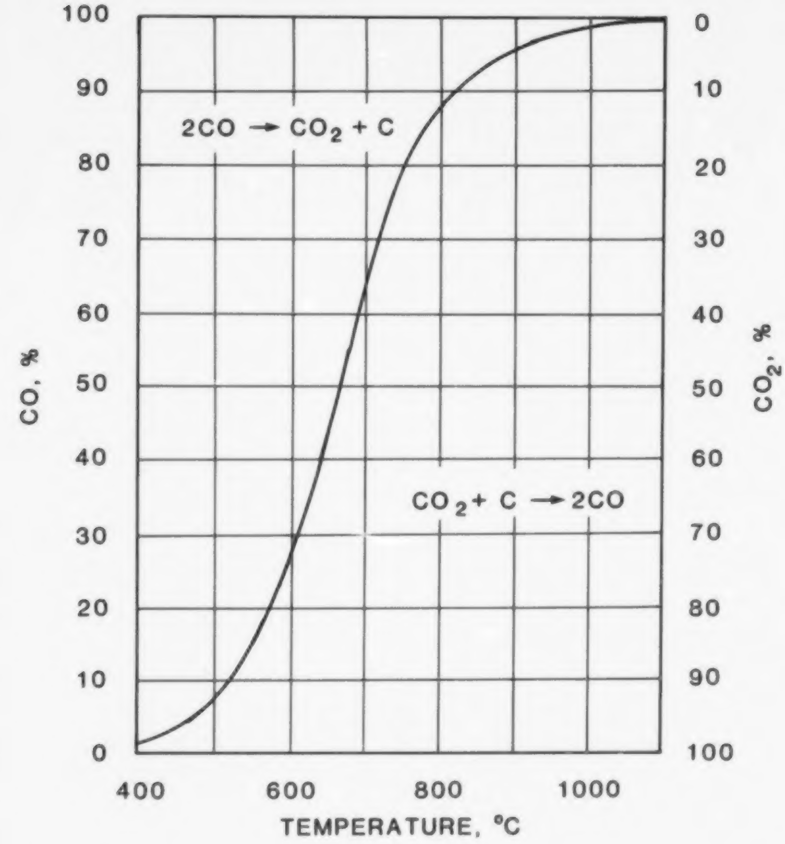


Figure 18. Equilibrium curve for Boudouard's reaction at 1 atmosphere pressure (19).

Once determined, the optimum internal gasifier dimensions are specific to the size of the gasifier, fuel tested, and air input rates. Recommended internal gasifier dimensions for various small wood gasifiers were developed by Nordstrom (39). Though these dimensions were determined for wood fueled gasifiers, they may be used as an initial estimate of the optimum dimensions for sludge/wastepaper fuels.

Size of fuel hopper and char pit - The fuel hopper (with extension) and the char pit have capacity for run length of about 90 minutes at a fuel rate of 80 kg/hr. Though these capacities were adequate for the experimental work described in this report, they are not sufficient for more detailed system analysis, which is a logical extension for this work.

To obtain extended uninterrupted run lengths a continuous flow system could be used. However, for pilot scale experimental work a continuous flow gasifier is a needless expense. Additional valves necessary for continuous operation are very expensive and subject to leakage. Extended run lengths can be obtained by enlarging the fuel hopper and char pit capacities.

The fuel hopper capacity can be enlarged by simply bolting an extension on the existing fuel hopper. Care must be taken in the design of the fuel hopper extension to avoid fuel bridging problems.

The enlargement of the char pit is more complex, involving either a complete redesign of the base of the gasifier or the addition of an auger system to the present char pit. Because a constant char level can be maintained the auger system seems most desirable. With the current design, increases in the char level caused increases in particle entrainment in the producer gas. During several gasifier runs it was noted that as the char pit became full, a noticeable deterioration of the producer gas quality occurred, caused by an increase in the amount of particulate matter in the gas. Therefore, to obtain valid particle size and particle loading rate data an auger system should be added to the existing char pit.

Full Scale Gasifier Systems for Small Communities - At present there are no full scale gasifier systems operating with sludge/wastepaper fuels. Thus to acquire a full scale gasifier system that can be used in a small community, commerically available gasifier systems originally designed to operate on wood fuels may be purchased and modified or a gasification system specially design for sludge/wastepaper gasification may be designed and manufactured. A brief review of commercially available gasifier systems and basic design concepts for construction of sludge/wastepaper gasifiers are discussed below.

Commercially Available Gasifier Systems - Kjellstrom (31) reports that there are two companies which manufacture complete gasification systems in the 100 to 1000 kW range. They are: Inbert Energitechnik Gmbh (22), and Moteurs Duvant (36). Addresses for each company are found in the references. Reed (45) has developed a directory for air biomass gasification systems, both commercial and research.

Inbert Energietechnic Gmbh markets complete gasification systems from 200 to 1000 kW_e. Dual-fuel diesel engines are used in the Inbert system. Inbert has had a great deal of experience in the manufacture of gasifiers. Over 500,000 gasifier of all sizes have been built in the last forty years. Recent correspondence (22) indicates that prices for Inbert gasification units range from 500 DM/kW for the 1000 kW_e plant to 1000 DM/Kw for the 200 kW_e plant. It is assumed that the price quoted by Inbert does not include the cost of the engine/generator set (22).

Moteurs Duvant offers complete gasifier/engine/generator systems in the 200 to 740 kW_e range. Moteurs Duvant is primarily an engine manufacture and their gasifiers are designed to work with their engines. The Moteurs Duvant gasification system uses a dual flow principle and requires a match box to brick sized fuel. Kjellstrom (31) reports that the cost for a complete plant (excluding shipping, installation, and test operation) is 4000 Fr/kW for a 200 kW plant and 2500 Fr/kW for a 740 kW plant.

Design of Sludge/Wastepaper Gasification System for Small Communities - The development of a detailed gasification system design is a complex process requiring a great deal of time and experimentation. Clearly, it is beyond the scope of this project to develop a detailed gasifier/engine/generator system design. However, basic design criteria that influence the operation, performance, and cost of a sludge/wastepaper gasification system for small communities are discussed below.

Basic gasifier system design criteria can be developed by analyzing the economic and social constraints present in a small community. The most important factor to be considered is overall system cost. Small communities do not have a large tax base and therefore cannot afford complex and expensive systems. As well as lacking the means to finance projects with a large capital investment, small communities do not always have personnel available to perform sophisticated repairs and maintenance on complex systems. Thus, criteria for a small community gasification system are that it must be low in capital cost, and be simple to operate and maintain.

In a small community, the operation of a gasifier system 24 hours per day is not necessary. A gasifier system that is designed to operate only a fraction of the day can be utilized to sell peak or partial peak power to the local power company.

Finally, highly automated gasifier systems are not necessarily needed in small communities because of the availability of relatively cheap, unskilled labor.

Therefore based on the technical requirements presented earlier in this report and the economic and social factors discussed above a gasifier/engine/generator system with the following characteristics is proposed to generate electricity from sludge/wastepaper fuels.

1. The gasifier/engine/generator system should be located at the local wastewater treatment plant. The need to transport the sludge great distances, which is expensive, would be eliminated. Wastewater can be used to cool and scrub the producer gas as part of the clean-up system. Scrubber liquid could be recycled to the head of the plant for treatment. Waste heat from the engine exhaust could be used to heat the wastewater sludge digestors while the digestor gas generated in sludge digestors could be fed to the engine. In many smaller communities, excess digestor gas is frequently flared because the capital investment for energy conversion exceeds the value of the energy produced. Finally, wastewater treatment personnel may be used to monitor and maintain gasifier system, in addition to their other duties.

2. A downdraft gasifier should be used because of its ability to generate a producer gas low in tar vapor. Because of the difficulty in sizing-up downdraft gasifiers, multiple gasifiers operated in parallel should be used when a larger capacity is needed. A parallel gasifier configuration will assure a producer gas low in tar vapor and allow a large turn-down ratio.

3. The gasifier should be operated in a suction mode rather than in an air blown mode. The pilot scale gasifier system discussed in this report was operated in an air blown mode. Many of the gasifiers used on vehicles during World War II were operated in the suction mode. In suction gasifier systems, the engine draws the gas into and through the gasifier. Because a significant pressure drop exists in the gasifier and clean-up system, the engine experiences a power loss. To eliminate engine power loss a compressor should be placed in the producer gas stream, located downstream of the clean-up system and upstream of the engine. The presence of the compressor will permit the gasifier to operate in the suction mode and allow the engine to be supercharged if desired. Because the compressor is located downstream of the gas clean-up system, producer gas impurities and heat, which would normally damage the compressor, would be removed.

   The advantages of operating the gasifier in a suction mode are significant. First, because the gasifier is under vacuum everything leaks into the gasifier, eliminating CO poisoning concerns and producer gas/tar vapor odors. Kaupp (29) visited a gasifier system in Iberra Cruz, Phillipines, which was located indoors. Finally, because the gasifier is under suction a sealed fuel hopper is not necessary. Therefore the fuel level in the fuel hopper can be monitored visually. More importantly, the fuel can be loaded into the fuel hopper using a simple and inexpensive conveyor system. This feature eliminates the need for expensive and frequently troublesome gas tight feed mechanisms and valves.

4. The gasification system should be operated in a batch mode rather than a continuous mode. A batch mode gasification system would combine the fuel conveyor system described above with an enlarged char pit, eliminating the need for a char removal mechanism. The char pit should have sufficient volume to contain all the char produced during an operating day. At the end of the operating day the char pit would be emptied. The operating day would be scheduled so that the gasifier system is operated when the peak power rates are in effect.

5. A dual-fuel diesel engine is recommended to convert producer gas into mechanical energy. Though a small amount of diesel fuel (about 15 percent of the overall energy input) needs to be added to the producer gas to aid in combustion, the proven reliability of dual-fuel diesel engines operated with producer gas is important. Besides proven reliability, the dual-fuel diesel can be changed from a dual-fuel mode to a pure diesel mode automatically. This feature could provide assurance to the local power company that power will be supplied to the local grid, despite any unscheduled gasifier down-time. Such assurances may be necessary in obtaining favorable electric power rates for sale to the local power company.

AIR POLLUTION EMISSION TESTS

An air pollution emissions test was conducted on the gasifier burner system during Runs 26, 27, 28-A, and 28-B. The services of Engineering Science (ES) were engaged by EPA-MERL to conduct the air pollution emission test. Both the producer gas stream and the burner flue gas stream were characterized with the following tests: particulate loading, particle size distribution, gas composition, gas flow rate, and particulate characterization sampling. In addition the burner flue gas stream was also tested for SO_2, total hydrocarbons, and NO_x. Each aspect of the emission test is reviewed briefly below. A summary of the draft report prepared by ES (15) is found in Appendix D. Modification of the results of the Engineering-Science Summary Report due to incorrect data inputs are also discussed below.

Particle Emission Test

A modified EPA Reference Method 5 test was used to determine the particle emissions in both the producer gas and the burner flue gas (See Appendix D). In reviewing the input data used to calculate the particle loading rate in the producer gas, an error was found. The error involves the producer gas molecular weight used in the calculations. The source of the error is an incorrect producer gas composition was used to calculate the producer gas density. ES based its calculation on Orsat analysis data taken during the test. The Orsat analysis data taken by ES differ greatly from both "typical" and measured producer gas composition values. In addition, hydrogen fraction of the producer gas was not taken into account. To obtain more exact producer gas flowrates, the molecular weight of the producer gas was corrected based on the producer gas composition values reported in Table 9. The corrected producer gas flowrates were calculated from the value reported by ES by using the following formula:

$$Q_{cor} = Q_{ES}\sqrt{\frac{MW_{ES}}{MW_{cor}}}$$

where Q_{cor} = corrected producer gas flowrate

Q_{ES} = producer gas flowrate reported by Engineering Science

MW_{ES} = producer gas molecular weight reported by Engineering Science

MW_{cor} = producer gas molecular weight based on compositional values from Table 7.

From the computations shown in Table 9 it can be concluded that the producer gas flowrates reported by Engineering Science are about 7 percent low. However, the corrections of the producer gas flowrates do not affect the burner flue gas flowrates because the tests were run independently.

Table 9

MODIFICATIONS OF PRODUCER GAS FLOWRATES MEASURED BY ENGINEERING SCIENCE

Item[a,b]	Run No.			
	26 (PG-M5-1)	27 (PG-M5-2)	28-A (PG-M5-3)	28-B (PG-M5-4)
MW_{ES} (lb/lb•mole)	28.00	28.17	27.93	28.09
MW_{cor} (lb/lb•mole)	24.45	24.46	24.25	24.25
Q_{ES} (ACFM)	304	306	357	339
Q_{ES} (DSCFM)	112	110	121	117
Q_{cor} (ACFM)	325	328	383	365
Q_{corr} (DSCFM)	120	118	130	126
$\frac{Q_{cor}}{Q_{ES}}$	1.070	1.073	1.073	1.076

[a] English units are reported here to allow for comparison with Particle Emission Data Report Sheets in Appendix D

[b] ES = Engineering Science, cor = corrected, ACFM = actual cubic feet per minute at stack conditions, DSCFM = dry standard cubic feet per minute at 68°F and 29.92 in Hg

One of the most important air pollution parameters for incinerators is the particle emission rate. Because the gasifier-burner system has the same objective as an incinerator it is important to compare their respective particle emission rates.

The particle emissions summary is found in Table D-2 of Appendix D. The particle concentration emissions from the producer gas burner for Runs 26, 27, 28-A, and 28-B are reported in Table 10. The federal standard for particle emission rates for an incinerator is 0.189g/dscm (grams per dry standard cubic meter, standard conditions are at 20°C and 1 atmosphere pressure) corrected to 12 percent CO_2 (57). Thus the producer gas burner system met the Federal Standards for particle emissions in an incinerator without a wet scrubber. Though the level of particle emissions is dependent on the design of the burner (or boiler), it can be inferred, from the data presented, that gasifiers in a boiler application could meet federal particle emissions standards with minimal clean-up equipment.

NO_x and Noncondensible Hydrocarbon Test Results

The results of tests conducted on the burner flue gas to determine the emission rate of NO_x and noncondensible hydrocarbons are summarized in Table D-3 in Appendix D. The NO_x and noncondensible hydrocarbon emission rates are based on flowrates measured during the particle emission tests. NO_x concentrations ranged from 60 to 115 ppm with average daily concentrations of 86.2, 79.2, and 80.9 ppm for Runs 26, 27, and 28 respectively. Noncondensible hydrocarbon concentrations (based on hexane) were less than 1 ppm except during a brief period during Run 27. There are no federal standards for NO_x and noncondensible hydrocarbons emission for incinerators.

SO_2 Test Results

Tests conducted on the burner flue gas to determine the approximate emissions of SO_2 are summarized in Table D-4 in Appendix D. The SO_2 conentrations ranged from .037 to .098 g/dscm for Runs 26, 27, and 28. There are no federal SO_2 emission standards for incinerators.

Characterization Samples

Samples of the fuel, char, and fly ash collected in the high efficiency cyclone, and particulate matter collected on filters were taken for analysis. Analysis of the samples collected was performed by EPA in Research Triangle Park. The results of these analyses were not made available for presentation in this report.

Particle Size Distribution

Particle size distribution determinations were made of the particles in the producer gas and burner flue gas using an Anderson 2000 6-Stage Impactor. Results of the particle size determinations are shown in Figures D-1 and D-2 in Appendix D.

The results of the particle size distribution determinations conducted on particles in the producer gas are in error. The error is due to an incorrect producer gas composition that was input into a computer program used by ES to calculate the particle size distribution. As discussed earlier, the producer gas composition reported by ES is incorrect because hydrogen was not measured. The omission of

Table 10

PARTICLE EMISSION RATES FROM THE PRODUCER GAS BURNER

Item[a,b]	Gasifier Run No.			
	26 (SO-M5-1)	27 (SO-M5-2)	28-A (SO-M5-3)	28-B (SO-M5-4)
Flowrate (dscm)	14.56	21.14	19.32	17.08
Particle Concentration (g/dscm)	0.0630	0.0490	0.0287	0.0471
CO_2 in Flue Gas (%)	4.60	4.80	5.05	5.20
Particle Concentration Corrected to 12% CO_2 (g/dscm)	0.1643	0.1225	0.0682	0.1087

[a] g/dscm = grams per dry standard cubic meter

[b] Standard conditions at 20°C, 1 atmosphere pressure

hydrogen from the producer gas composition alters the results of the particle size distributions reported in Figures D-1 and D-2 of Appendix D.

To obtain correct particle size distributions, the cut diameters at each stage of the impactor can be corrected to reflect the actual gas composition. Raabe (42) states that aerodynamic diameters for inertial impactors can be corrected for changes in gas composition by using the following equation:

$$D_{50-2} = D_{50-1} \times \left(\frac{\mu_2}{\mu_1}\right)^{1/2}$$

where D_{50-2} = aerodynamic cut diameter for gas 2

D_{50-1} = aerodynamic cut diameter for gas 1

μ_2 = dynamic viscosity for gas 2

μ_1 = dynamic viscosity for gas 1

To find the viscosity of the gas mixture the equation developed by Herning and Zipperer (20) can be used if the H_2 content of the gas is less than 25 percent. If the H_2 content of the gas is greater than 25 percent, Wilke's correlation (62) should be used (8).

Using the relation developed by Herning and Zipperer (20) to calculate the gas viscosities and Raabe's equation (42) stated above, the impactor stage cut diameters originally calculated by ES were corrected to reflect the correct gas composition. These results are presented in Table 11. Despite the large difference in gas composition, the cut diameters calculated by ES differ from the corrected cut diameters by less than 2 percent.

FEASIBILITY OF USING GASIFIER CHAR AS A SOURCE OF POWDERED ACTIVATED CARBON

Char samples from eight gasifier runs (described in Reference 61) were analyzed for their effectiveness as a replacement for powdered activated carbon. A summary of the test results of the work described in Reference 12 is discussed below.

Activated carbon can be used in several ways to remove pollutants from wastewater. Though granular activated carbon is used usually in adsorption systems, powdered activated carbon has applications in numerous treatment schemes (5,10,11,53,62). Adsorptive properties of char produced from the gasification of solid wastes have been studied (5,48,53,56) with varied results.

Experimental Procedure

To characterize the effectiveness of the use of gasifier char as a replacement for powdered activated carbon the following tests were conducted on ground and classified char samples: proximate analysis, ultimate analysis, apparent density, methylene blue number, iodine number, rate of adsorption of TOC, relative TOC

Table 11

CORRECTION OF PARTICLE SIZE DISTRIBUTION DATA

Item		Run 26	Run 27	Run 28-A
Dynamic viscosity using ES gas data, micropoise[a]		314	318	316
Dynamic viscosity using UCD gas data, micropoise[a]		304	308	308
$\left(\frac{\mu_{UCD}}{\mu_{ES}}\right)^{1/2}$[b]		0.984	0.984	0.987
Corrected cut diameter in microns at stage:	1	13.36	12.17	12.05
	2	8.37	7.62	7.55
	3	3.92	3.56	3.52
	4	2.54	2.31	2.29
	5	1.31	1.19	1.17
	6	0.64	0.58	0.57

[a] Dynamic viscosity calculated at impactor temperature using equation developed by Herning and Zipperer (20)

[b] Cut diameter correction factor presented by Raabe (42)

reduction factor (TOC RF), settling tests, and scanning electron microscopy. The procedures for proximate and ultimate analysis are reviewed in Table 2. The methylene blue number and iodine number are derived from color adsorption isotherm tests used to correlate the ability of the char to adsorb low molecular weight substances. The TOC (total organic carbon) removal rate was conducted to estimate the contact time necessary for practical application in wastewater treatment. The most important char characterization test is the Relative TOC RF, which is used as an indicator of relative efficiency of removal of TOC with respect to a reference activated carbon (Calgon BL). Settling tests were conducted using the jar test procedure. A scanning electron microscope was employed for morphological examination of the microstructure of the char surface.

Results

Results from the determination of the chemical composition of the char from gasified wastepaper and various mixtures of sludge and wastepaper are shown in Table 12. The results of several empirical tests for measuring the adsorptive capacity of activated carbon are summarized in Table 13.

Discussion of Results

In general, the factors that effect the quality of the adsorptive characteristics of the char product are the nature of the starting material and the type of reactor used to produce the char. The criteria for a starting material of good quality adsorbent are high carbon content and low ash content. Because of their low ash content wood chips would be expected to yield the highest quality adsorbent of the chars tested. Based on the experimental values of the TOC RF in Table 13, it can be seen that the best starting material was woodchips. It was expected that the starting material with the largest percentage of sludge (which contains the most inert material) would yield the poorest quality absorbent. Also, it was expected that the adsorption capacities of the other chars from wastepaper and sludge/wastepaper mixtures would increase with decreasing sludge contents of these mixtures. However, from Table 13 it can be seen that no simple relationship exists between the adsorptive capacity and the sludge content of the starting material. The chars from Runs 4, 9, 10, and 12 were shown to follow the predicted trend of decreasing adsorbability. However, the values for the chars from Runs 6 and 11 were inconsistent. It is likely that these inconsistencies resulted from conditions under which the starting material was activated.

The adsorptive characteristics of the thermally gasified carbonaceous materials are highly dependent on the type of reactor used for activation, although all chars tested posess some degree of activity. However, as discussed earlier, some sludge/wastepaper mix chars (Runs 6 and 11) were observed to have adsorptive capacities that were inconsistently higher than those observed for chars of similar starting materials. Further, two chars of the same sludge/wastepaper composition, from Runs 6 and 9, were observed to have completely different adsorptive characteristics (see Table 13). For example, the char from Run 9 had methylene blue number of 16 compared with the value of 69 for char from Run 6. These anomalies can be attributed to nonuniform activation, a problem commonly associated with packed-bed reactors.

Table 12

CHEMICAL COMPOSITION OF GASIFIER CHARS USED IN ACTIVATED CARBON STUDIES

Run #	Fuel Type	Energy Content (Dry Basis, HHV) (MJ/kg)	Ultimate Analysis (% by weight)						Proximate Analysis % by weight			
			C	H	O	N	S	Residue	MC	VCM	FC	Ash
6	Almond shells/ 10% sludge/ wastepaper	13.11	45.31	0.48	0.0	0.20	62.2[a]	0.0	0.25	1.23	37.63	60.89
8	Wastepaper	8.52	28.81	0.29	3.78	0.17	0.05	66.9	1.19	5.51	20.73	72.57
9	10% sludge/ wastepaper	22.15	35.78	1.00	0.0	0.21	0.05	64.7[a]	1.20	6.50	49.40	42.90
10	15% sludge/ wastepaper	24.37	70.38	1.49	6.12	0.33	0.18	21.5	0.88	3.39	46.16	49.56
11	20% sludge/ wastepaper	27.60	79.01	0.75	2.37	0.27	0.20	17.4	0.70	2.60	16.90	79.80
12	25% sludge/ wastepaper	24.38	68.55	1.36	2.68	0.62	0.19	26.6	0.60	5.60	18.50	75.30

MC = Moisture content, VCM = Volatile combustible matter, FC = Fixed carbon

[a] As oxides, therefore total is greater than 100%

Table 13

SUMMARY OF ADSORPTIVE CHARACTERISTICS OF POWDERED ACTIVATED CARBONS AND GASIFIER CHARS

Item	Gasifier Run Number	Apparent Density g/cc	Methylene Blue Number, mg/g	Iodine Number, mg/g	Relative TOC Reduction Factor	
					Primary effluent	Secondary effluent
Calgon BL	—	0.61	155 (280[a])	650 (920[a])	1.00	1.00
Hydro-Darco H	—	0.56	50	330	0.86	0.88
Wood chip char	2	0.45	59	260	1.23	1.25
Almond shell char	6-A	0.33	16	170	0.59	.85
Wastepaper char	8	0.51	36	210	0.20	.49
Almond shells/10% Sludge/wastepaper char	6	0.45	69	390	0.81	1.00
10% sludge/wastepaper char	9	0.45	16	120	0.17	0.54
15% sludge/wastepaper char	10	0.50	16	145	0.20	0.46
20% sludge/wastepaper char	11	0.53	20	200	0.63	1.00
25% sludge/wastepaper char	12	0.50	< 8	< 60	0.13	0.49

[a] From Roberts, et al (48)

Another possible cause for a nonuniformly activated sample from a downdraft gasifier is related to the activating agent used: air. Activation of solid wastes with air has been difficult to accomplish consistently in practice (5,56). Difficulty with air-activation is due to the inability to control burning effectively. To alleviate this problem it has been stated that temperatures must be so high and air introduced in such a way that air (oxygen) will react with CO and H_2 before the carbon in the feed is reached (5).

Based on results reported in Table 13 it may be concluded that chars from Runs 2, 3, 6, and 11 were as effective in removing TOC from wastewater as the commercially available activated carbons Calgon BL and Hydro-Darco H. Based on the results of the adsorption rate studies using secondary effluent, chars from gasified solid wastes were found to have a similar adsorption rate to that of commercial activated carbon. Also studies conducted as part of this work showed that gasifier chars and commercial activated carbon have similar settling properties.

The overall feasibility of gasifier char recovery as a substitute for powdered activated carbon in the treatment of wastewater is dependent on many factors. First, it must be established that the char has a suitable adsorption capacity, adsorption rate, and settleability for the wastewater being treated. It should be noted that the gasifier is designed to optimize combustible gas production which, as discussed earlier, occurs when the carbon content of the char is minimized. Because char with good adsorptive properties contains a large fraction of carbon, the production of a high quality producer gas and a char that has good adsorptive properties for wastewater treatment may to be mutually exclusive goals.

Conclusions

The following conclusions were reached as a result of the evaluation of the adsorptive properties of residual chars from the gasification of sludge and wastepaper fuels.

1. Residual chars from the gasification of some wastepaper fuels had adsorptive capacities for TOC comparable to that of commercial activated carbon.

2. The adsorptive capacities of gasifier chars for TOC are highly dependent on the operating conditions of the downdraft gasifier.

3. Nonuniform activation of the char most likely occured in the downdraft gasifier.

4. Gasifier chars have adsorptive rates and settleability comparable to those of commercial activated carbon.

5. The high ash contents (from 43 to 80 percent) of the sludge/wastepaper chars may preclude their commercial application in the treatment of water and wastewater.

OPERATION OF A SMALL DIESEL ENGINE WITH PRODUCER GAS

A series of gasifier tests (Runs 14, 15, 16) were conducted to evaluate the performance of a small diesel engine operated in a dual-fuel mode with producer gas. As part of the test the diesel engine was also operated with synthetic biogas (60 percent CH_4, 40 percent CO_2) in a dual-fuel mode and in the normal diesel fuel mode. Performance curves comparing torque, speed, power, air ratio, effective efficiency, and exhaust temperature were constructed for each mode of operation.

Producer gas, generated from the gasification of densified wastepaper, was cleaned by a fiberglass filter and a condensor. The gas was fed to the engine with a modified natural gas engine carburetor. In both the biogas and producer gas dual fuel modes, 15 to 24 percent of the input fuel energy was diesel fuel. It was found that the practical power output in the dual modes was 30kW (86 percent) with biogas, and 25 kW (71 percent) with producer gas from the gasifier as compared to 34 kW (100 percent) with normal diesel operation. A description of all aspects of these tests may be found in Reference 40.

SECTION 6

ECONOMIC FEASIBILITY OF SLUDGE/WASTEPAPER GASIFICATION IN SMALL COMMUNITIES

An analysis of the economic feasibility of the use of sludge/wastepaper gasification systems in small communities was first presented in Reference 4 and then expanded and updated in Reference 54. The results of the economic feasibility of sludge/wastepaper gasification originally published in Reference 54 are presented in this chapter in two parts dealing with: a description of the sludge/wastepaper gasification system used in the study and an economic analysis.

SLUDGE/WASTEPAPER GASIFICATION SYSTEM DESCRIPTION

An alternative system for the disposal of sludge that can be used by small communities involves the gasification of wastewater sludge, source separated wastepaper, and wood chips. A description of the gasification system and a discussion of important criteria influencing the system design are presented below.

Gasification System Description

The gasification system shown in Figure 19 consists of three different process elements: collection, fuel processing, and energy recovery.

Collection - The collection process consists of collection of source separated wastepaper, dewatering of sludge, and the procuring of wood chips. These items will be mixed and processed to form the fuel used in the gasifier.

The collection of source separated wastepaper is accomplished by utilizing a separate collection vehicle to collect source separated wastepaper from residences. At the end of the collection day or when fully loaded, the collection vehicle is driven to and unloaded at the city's wastepaper processing facility (located at the wastewater treatment plant). There it is stored until utilized in the fuel cube process.

For the purpose of this study, it will be assumed that the wastewater will be treated at an activated sludge wastewater treatment plant. Wastewater sludge from the treatment plant must be dewatered prior to its utilization as a gasifier fuel.

Digested sludge is the product of the activated sludge treatment process and is dewatered using a filter belt press. A polymer is added to the sludge to facilitate the dewatering process. It is assumed that the sludge solids content of 30 percent can be achieved.

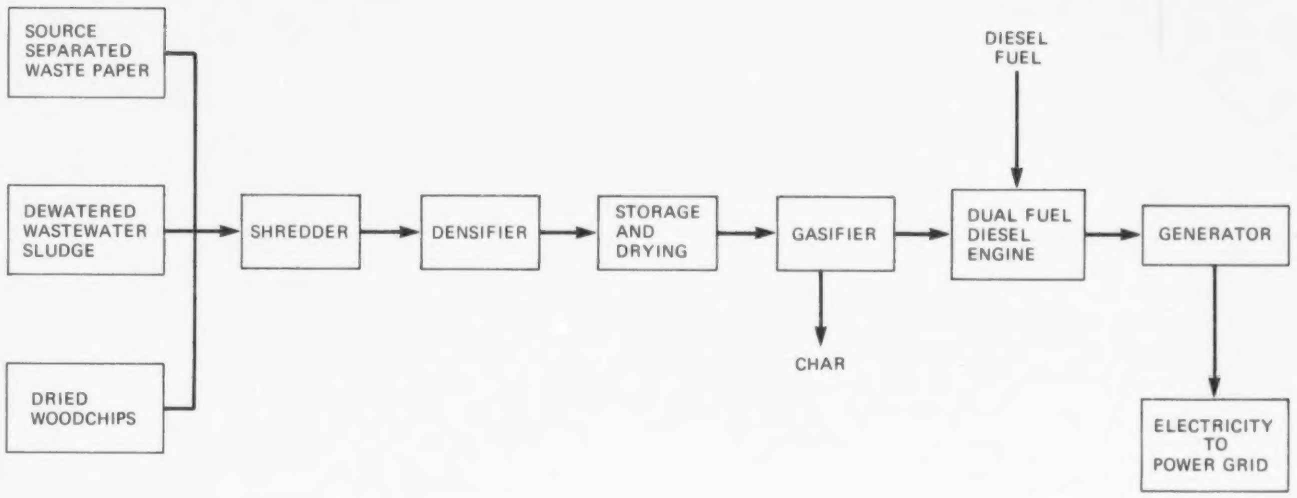

SOURCE SEPARATED WASTE PAPER
DEWATERED WASTEWATER SLUDGE
DRIED WOODCHIPS
SHREDDER
DENSIFIER
STORAGE AND DRYING
GASIFIER
CHAR
DIESEL FUEL
DUAL FUEL DIESEL ENGINE
GENERATOR
ELECTRICITY TO POWER GRID

Figure 19. Process diagram of a sludge/wastepaper gasification system for a small community.

Dry wood chips are purchased from local lumber or planer mills to supplement the wastepaper and sludge. Wood chips are added to the sludge/wastepaper mixture to adjust the ash and moisture content.

Fuel Processing - To produce a gasifier fuel with suitable size and density characteristics, the dewatered sludge, wastepaper and wood chips must be mixed, shredded, and densified. A typical fuel cube processing system, such as manufactured by the Papakube Corp. of San Diego, California, is shown in Figure 10. To date, more than 9 tons of densified sludge/wastepaper fuel cubes have been produced for this project using the Papakube system.

The sludge/wastepaper/wood chip processing facility consists of a shredder, densifier, and a fuel cube drier which also functions as storage for the fuel cubes. Predetermined quantities of dewater sludge, wastepaper, and wood chips are fed onto a conveyer that passes through a magnetic separator and leads to the shredder. The shredder reduces the size of the wastepaper and wood chips and mixes the sludge, wastepaper, and wood chips together to form a relatively homogeneous mixture. The shredded mixture passes through a metering system and is fed into the densifier. The densified fuel cubes are conveyed to a hopper where they are dried and stored until needed.

Energy Conversion - The chemical energy in the densified fuel cubes is converted into electricity by utilizing an energy conversion system consisting of a downdraft packed-bed gasifier, a dual-fuel engine, and an electric generator. Fuel cubes from the storage hopper are conveyed to the gasifier. The fuel cubes are converted into producer gas and char in the gasifier. The char is removed from the gasifier, cooled, and taken to a landfill. The producer gas is cooled, cleaned, and fed to a dual-fuel diesel engine. To aid in the combustion of the producer gas, 15 percent of the energy input to the dual-fuel diesel engine is provided by the diesel fuel. The dual-fuel diesel engine-generator produces electricity, which can be used at the wastewater treatment plant or sold to the local utility.

Important Technical Factors that Influence Sludge/Wastepaper Gasification System Design

There are several important technical factors that influence the design, cost, and thus the feasibility of a sludge/wastepaper gasification system in a small community. They are: fuel ash content, quantity of wastepaper collected, and moisture content of dewatered sludge.

Fuel ash content - As discussed earlier, the fuel ash content plays an important role in downdraft gasifier. In addition to lowering the energy content of the fuel, fuel ash, upon reaching its melting point in the gasifier and then cooling, forms slag. Excessive slag formations in a downdraft gasifier can block the flow of fuel and char through the gasifier and thus halt the gasification process. The tendency for slag formation is a function of reaction zone temperature, the composition of fuel ash, and the percentage of fuel ash (29). After extensive testing with various agricultural residues, Jenkins found that the upper limit for fuel ash percentage was about 6 percent (dry basis) (26). From the results presented in Section 4 it was found that sludge/wastepaper fuels with an average fuel ash content of 4.85 percent (dry basis) were gasified without significant slag formation.

Because it is possible to reduce the tendency for slag formation by temperature control with water injection and by varying the grate rotation rate, the maximum feasible fuel ash content may be higher than those values previously cited. However, for the purposes of this study, it is assumed that the maximum feasible fuel ash content in a downdraft sludge/wastepaper gasification system is 5 percent (dry basis).

From a sludge disposal point of view, it would be ideal to gasify pure sludge. But because the ash content of wastewater sludge is 25-40 percent (35) the gasification of pure sludge in a downdraft gasifier is not feasible. To lower the overall fuel ash content, Vigil proposed mixing source separated newspaper with dewatered wastewater sludge (60). Unfortunately, there is not enough newspaper generated in a community to balance the corresponding production of sludge. The newspaper generation rate is estimated to be about 0.09 kg/person•day. There is about 5.5 times more wastepaper (newspaper, magazines, corrugated paper, etc.) generated daily than newspaper, but its ash content is also higher, 4-10 percent (58). If all the wastepaper generated in a community was collected and mixed with all the wastewater sludge generated, the resultant fuel ash content would be 8.2 percent (dry basis). This calculation is based on the following assumptions: 1) a municipal solid waste generation rate of 1.6 kg/person•day, 2) 33 percent of the municipal solid waste generated is wastepaper, 3) a dry sludge solids generation rate of 51 g/person•day, 4) the moisture content of the wastepaper is 6 percent, 5) the ash content of the wastepaper is 6 percent (dry basis), and 6) the ash content of the sludge is 30 percent (dry basis).

Because it is not possible to collect all the wastepaper generated in a community, the fuel ash content obtainable in an operational system would be higher. This effect is shown in Figure 20. It can be concluded that a mixture of wastepaper and wastewater sludge is an unsuitable downdraft gasifier fuel.

To derive a useable gasifier fuel from a mixture of wastewater sludge and source separated wastepaper, wood chips can be added to the mixture. Because the ash content of wood chips is low (0.1 - 3.0 percent dry basis), a fuel ash content of 5 percent (dry basis) can be achieved. The quantity of wood chips that needs to be added to the sludge/wastepaper mixture, as a function of the percent of the total wastepaper collected is shown in Figure 21.

Moisture Content of Dewatered Sludge - The dewatering of wastewater sludge is a very important process in a wastewater treatment facility. Dewatering is a physical unit operation used to reduce the moisture content of sludge. The cost of sludge dewatering accounts for a substantial part of the overall treatment plant cost.

Sludge dewatering is also very important in a gasification process because of the fuel moisture content specifications of the densification system. The fuel moisture content in the densification system is dependent on the type of and size of the material to be densified. For example the range of acceptable fuel moisture contents for the Papakube densification system is 15 to 25 percent with the optimum for sludge/wastepaper/wood chips estimated to be 18 to 20 percent (41).

For the purposes of this study, it is assumed that a filter belt press with polymer addition will be used to dewater the sludge. This device was chosen due

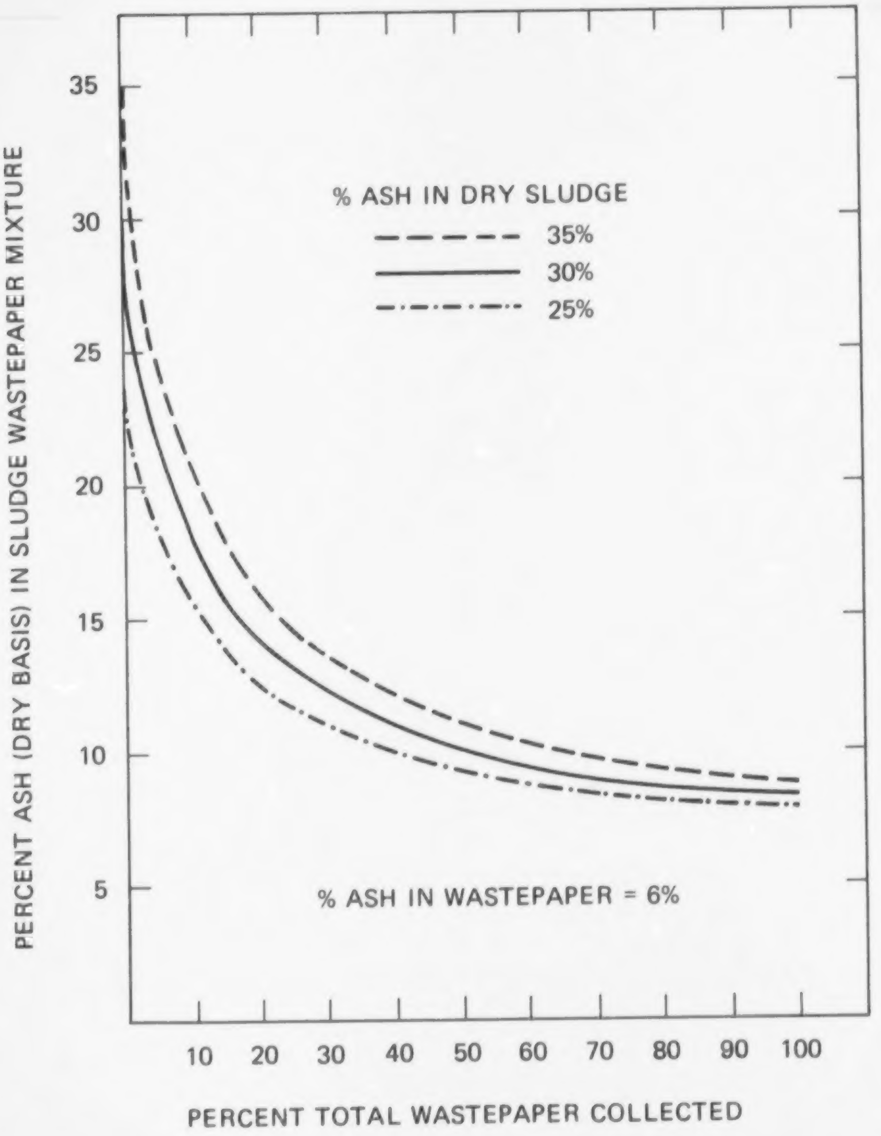


Figure 20. Variation of the percent ash in a sludge/wastepaper mixture as a function of the percentage of wastepaper collected.

75

TYPING GUIDE SHEET

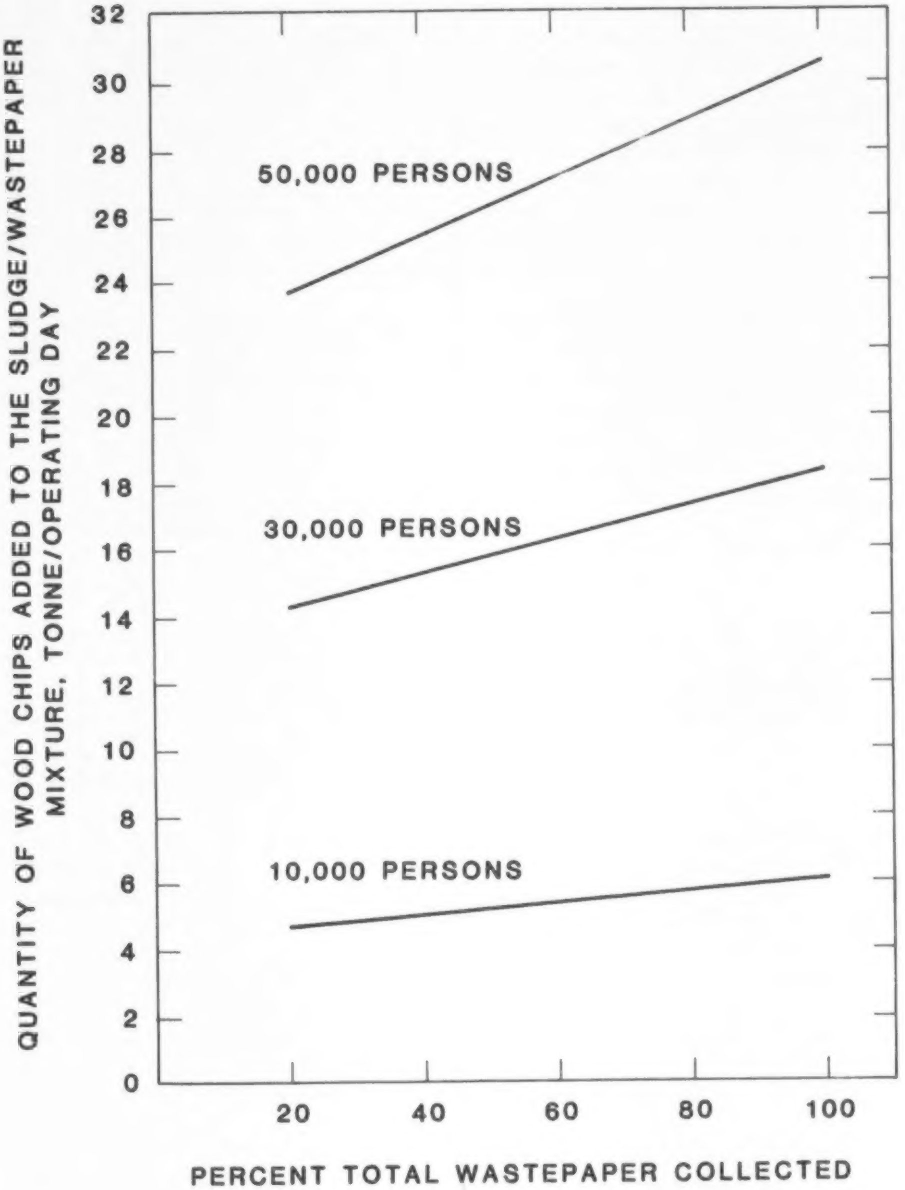


Figure 21. Quantity of wood chips that need to be added to the sludge/wastepaper mixture to maintain an ash content of 5%.

to its dewatering characteristics, cost, reliability (with 100 percent operator attention), and ability to interface with the densification system.

A fuel composed of all the dewatered sludge (moisture content of 70 percent) and wastepaper (moisture content of 6 percent) generated in a community would have a moisture content of about 22 percent. Unfortunately, it is not possible to collect 100 percent of the wastepaper generated in a community. Thus, the moisture content of the sludge/wastepaper mixture attainable in a community gasification system would be much higher. To obtain the desired fuel moisture content for the optimum densifier operation, dried wood chips can be added to the sludge/wastepaper mixture. The quantities of wood chips that need to be added to the sludge/wastepaper mixture are shown in Figure 22. For the purpose of this study, it is assumed that wood chips (moisture content of 10 percent) sludge (moisture content of 70 percent), and wastepaper (moisture content of 6 percent) are mixed in quantities so that a mixture with a moisture content of 20 percent is formed.

A graphical representation of the quantity of wood chips added to the sludge/wastepaper mixture to maintain a fuel ash content of 5 percent (dry basis) and a fuel moisture content of 20 percent is shown in Figure 23. It can be concluded that if less than 63 percent of the available wastepaper is collected the quantity of wood chips added to the sludge/wastepaper mixture is governed by the required fuel moisture content. Thus, if the sludge can be dewatered to a moisture content of less than 70 percent the quantity of wood chips added to the sludge/wastepaper mixture would be reduced. If, however, more than 63 percent of the available wastepaper is collected, the quantity of wood chips added to the sludge/wastepaper mixture is governed by the fuel ash content requirements.

Quantity of Wastepaper Collected - From Figure 23 it is evident that the percentage available wastepaper collected influences greatly the quantity of wood chips that are needed for a successful sludge/wastepaper gasification system. Because in many areas of the country, the cost of dried wood chips is high, the percentage of available wastepaper collected will influence significantly the economic feasibility of sludge/wastepaper gasification.

The recovery of wastepaper by source separation from residential areas requires participation of citizens to separate, bundle or bag, and place paper at the curb at regular intervals for collection. Though an increasing number of wastepaper collection programs are required by city ordinance (14), many programs are voluntary. Thus, people's attitudes toward a source separation program determine, to a large extent, the success and failure of the program. If a successful sludge disposal program is dependent on collecting a large fraction of the total wastepaper generated, then it is incumbent on local officials to inform and educate their citizens about the wastepaper recycling. The public must know the purpose of the wastepaper recycling program and the exact nature of their requested participation (14,51).

ECONOMIC ANALYSIS

To assess the economic feasibility of gasification as an alternative sludge disposal process, an economic analysis was performed on the gasification system described above for communities of 10,000, 30,000, and 50,000. The costs of sludge disposal by gasification were compared with the cost of sludge disposal by landfilling.

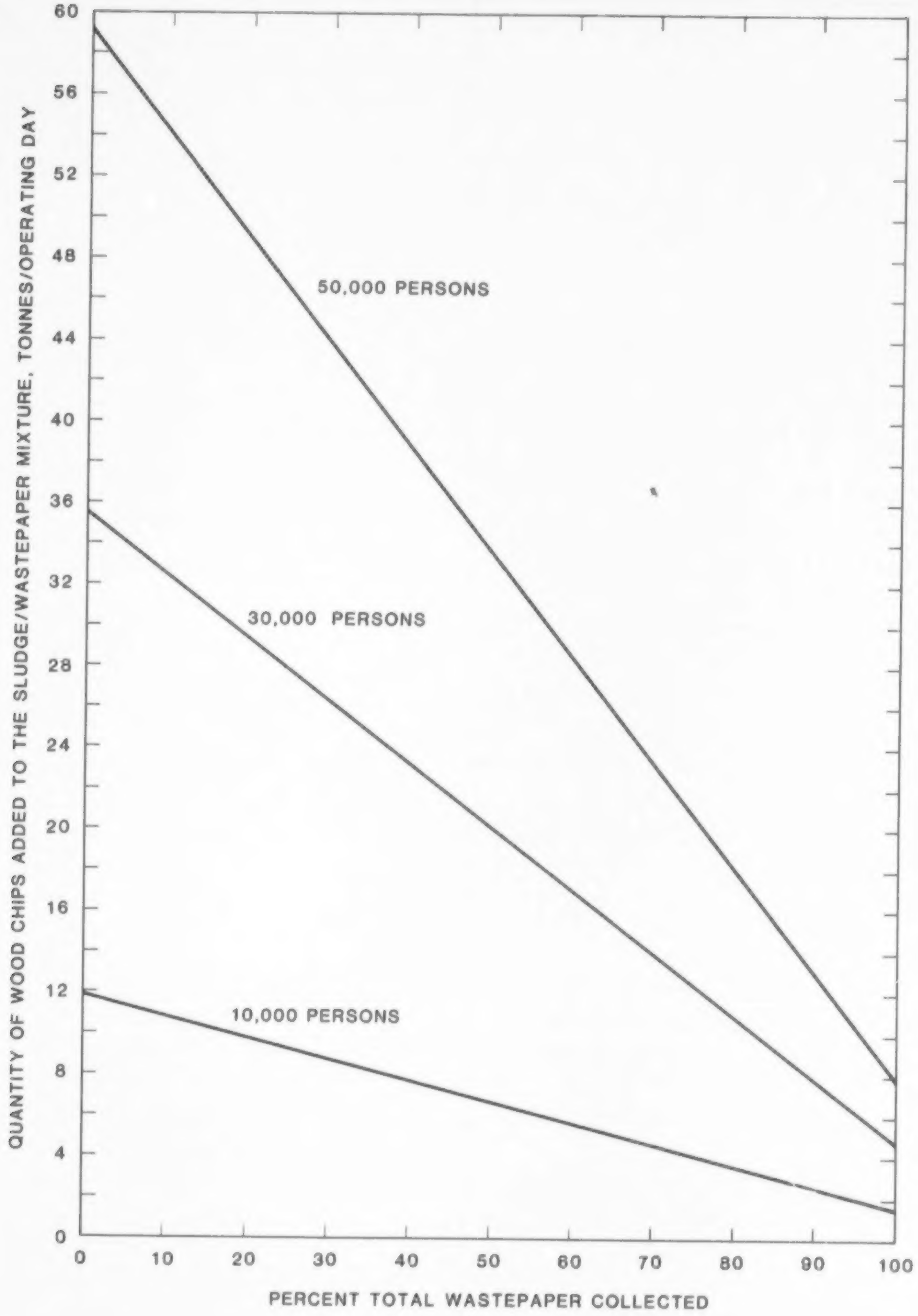


Figure 22. Quantity of wood chips that need to be added to the sludge/wastepaper mixture to maintain a moisture content of 20%.

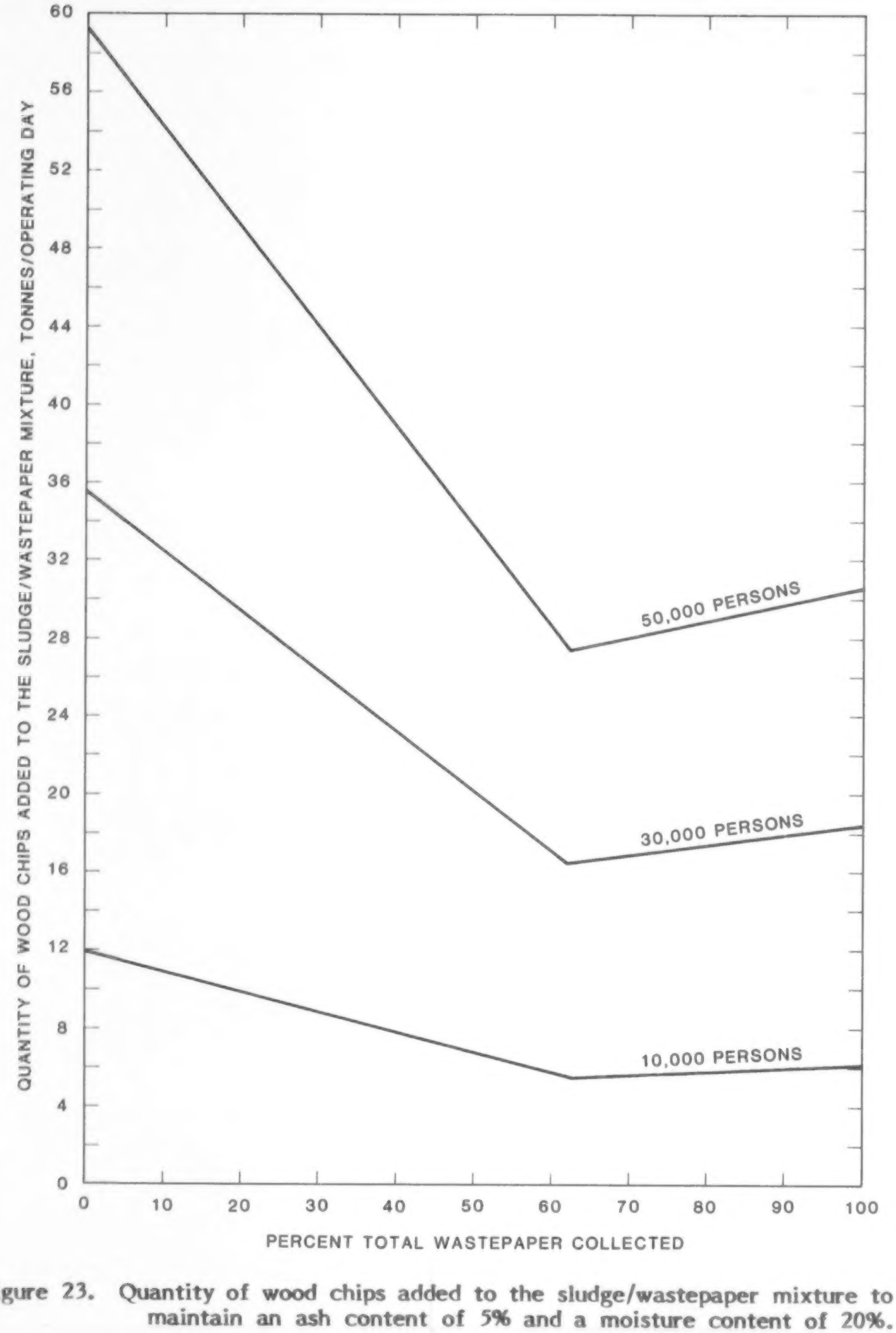


Figure 23. Quantity of wood chips added to the sludge/wastepaper mixture to maintain an ash content of 5% and a moisture content of 20%.

The methodology for analysis, sources of information and costs, key assumptions, cost summary, and conclusions to economic feasibility are discussed below.

Methodology of Analysis

The economic feasibility of sludge/wastepaper gasification in small communities is dependent on many parameters, which are technical, economic, and site specific in nature. During the course of this study it was determined that there are more than 50 parameters that affect the economic feasibility. To analyze the effect that each parameter has on the overall cost of gasification is beyond the scope of this paper. Therefore, the majority of the parameters are fixed and only the most important parameters were varied. The parameters that were varied are the cost of power, cost of wood chips, and community size.

The sensitivity of sludge/wastepaper gasification costs to power costs, woodchips costs, and community size was determined. A baseline cost was calculated for each community size by fixing the power cost at $.08/kWh, and the woodchip cost at $33/Mg (= $30/ton).

The sensitivity of sludge/wastepaper gasification costs to each parameter cited above is obtained by varying the parameter of interest while holding the remaining parameters fixed at the baseline cost. Two computer programs were written to calculate the sludge/wastepaper gasification system costs used in the sensitivity analysis. One program was used to calculate the cost of wastepaper collection. The second program was developed to calculate an energy balance and total annual costs for the sludge/wastepaper gasification system. These programs are found in Appendix E. Cost curves were developed for the net total annual cost and the net unit cost for sludge disposal by sludge/wastepaper gasification.

Landfilling of dewatered sludge is the most common method of sludge disposal utilized in small communities. To obtain a realistic comparison between sludge disposal operations, the cost of sludge disposal by landfilling is compared to the costs of sludge/wastepaper gasification.

Source of Information & Costs

Information and cost data used in this report were obtained from literature and published reports, communications with manufacturers and equipment suppliers, manufacturers catalogues, and consultants with practicing engineers and researchers. Due to the different bases of cost data, all literature derived costs are updated using an Engineering News Record Construction Cost (ENRCC) Index value of 3610 which corresponds to the value of the index in September 1981. The interest rate used in this analysis is 13 percent. Other costs were determined using September 1981 labor and fuel costs.

Wastepaper Collection - The methodology for the determination of the wastepaper collection costs was obtained from Reference 4. Also, local officials of the Davis Waste Removal Co. (13) and the Sacramento County Department of Public Works (49) were contacted concerning their wastepaper recovery systems and some of their suggestions were included in this analysis.

Wastewater sludge dewatering system - Information on capacity, preformance and cost of filter belt press was obtained from manufacturers. Costs associated with installation, engineering, contingencies, and construction were adapted from Reference 59.

Mixing/Shredding/Densifying - The basic design information as well as cost data were obtained almost exclusively from the Papakube Corporation, San Diego, California (41). To account for installation, engineering, and contingencies, 25 percent was added to the equipment cost.

Gasifier/Engine/Generator - Preformance data for the gasifier/engine/generator were from Kjellstrom who prepared an ecomonic analysis for the gasification of wood (31). The installed cost data for the gasifier/engine/generator systems was updated for use in this report.

Ash Disposal Cost - The methodolgoy used to determine the cost for the disposal of char was similar to that used to calculate wastepaper collection costs. However the truck used for the ash disposal is assumed to be borrowed from the city. Only the cost of truck maintenance and labor was charged to the system cost. It was assumed that the distance from the wastewater treatment plant to the landfill is 10 miles.

Sludge Disposal by Landfilling - Costs for the disposal of sludge by landfilling were obtained from Reference 3. A range of costs for sludge disposal by landfilling is shown in Table 14. The costs cited were updated using an ENRCC Index value of 3610.

Key Assumptions

The key assumptions used in this economic analysis are summarized in Table 15. However a complete list of all the assumptions used in the economic analysis of sludge/wastepaper gasification can be found in Appendix E.

Cost Summary

A summary of the cost data used to assess the feasibility of sludge/wastepaper gasification is presented below.

Calculation of Total Annual Costs - The method used to calculate the total annual cost and the total unit costs is discussed in this section. The cost components that make up the overall cost of a sludge/wastepaper gasification are: wastepaper collection, wastepaper processing, wood chip processing, sludge processing, fuel processing/gasification building, densification system, gasifier/engine/generator, energy credit, and ash disposal. The capital costs shown in Table 16 represent the sum of equipment costs, installation, engineering, contingencies and construction for each item. The annual capital cost is obtained by using a capital recovery factor based on an interest rate of 13 percent and the useful life of the item. Annual operation and maintenance costs include maintenance, repairs, labor, administration and overhead, fuel cost, power costs, and materials. An energy credit is obtained from the sale of electricity produced by the generator to the power utility. It is assumed that the unit price of electricity sold to the power utility is equal to the unit price of electricity purchased from the utility.

Table 14

ANNUAL COST FOR SLUDGE DISPOSAL BY LANDFILLING[a]

Annual Cost	Population		
	10,000	30,000	50,000
Minimum Annual Cost, \$1000/yr	20.5	61.5	102.5
Maximum Annual Cost, \$1000/yr	43.7	131.2	218.6

[a] Adapted from Reference 3.

Table 15

IMPORTANT ASSUMPTIONS FOR THE ECONOMIC ANALYSIS OF A SLUDGE/WASTEPAPER/WOOD CHIP GASIFICATION SYSTEM

Item	Units	Value
Wastepaper Collection		
Percent of total wastepaper recycled	%	40
Cost of labor	$/hr	10
Capacity of wastepaper collection vehicle	Mg/load	5.0
Number of persons on wastepaper collection crew	persons	1
Wastepaper collection pick-up time	min/residence	0.5
Sludge		
Moisture content of dewatered sludge	%	30
Ash content of dry sludge solids	%	30
Digested sludge generation rate	g/person·day	51
Wood Chips		
Moisture content	%	10
Ash content, dry basis	%	0.5
Cost, delivered	$/Mg	varies
Mixing/Shredding/Densification		
Equipment costs	$	138,700
Gasifier		
Maximum fuel ash content	%	5
Hot gas efficiency	%	75
Cold gas efficiency	%	70
Cost	$/kWh	1,000
Useful life	years	10
Dual Fuel Diesel Engine		
Efficiency for producer gas operation	%	36
Amount of diesel fuel injected	% fuel energy used by engine	15
Cost of diesel fuel	$/liter	.33
Generator		
Efficiency	%	93
Cost of power produced	$/kWh	varies

Table 16

EQUIPMENT CAPITAL COSTS FOR SLUDGE/WASTEPAPER/WOOD CHIP GASIFICATION SYSTEM

Item	Capital Cost[a]	Useful Life	Salvage Value, $	Reference
Wastepaper Collection Vehicle, diesel, 24' stake bed with lift	$27,000	10 years	6000	23
Wastewater Sludge Belt Press	$185,200	15 years[b]	none[b]	2
Shredder/Densifier	$92,400	10 years or 90718 Mg	none	41
Densification System (less densifier)	$92,500	10 years	none	41
Gasification/Densification Building	$161/m^2	15 years	none	47
Gasifier/Engine/Generator (total installed cost)	$1000/kWh	10	none	31

[a] Based on an ENRCC index value of 3610

[b] Value assumed

The net total annual cost of the sludge/wastepaper gasification system is the sum of the annual capital cost, annual operation and maintenance cost, and the energy credit. The net total annual costs are reported in terms of thousands of dollars per year ($1000/yr) and dollars per million grams of dry sludge disposed ($/Mg).

Sensitivity analyses - Sensitivity analyses of net total annual costs of the sludge/wastepaper gasification system are presented for each community size. The sensitivity of the net total annual cost to the power cost and wood chip cost for each community size are presented in graphical form in Figures 24, 25, and 26.

Conclusions Regarding Economic Feasibility

Based on the material presented in this chapter, the following conclusions concerning the economic feasibility of sludge/wastepaper gasification can be reached:

1. Given the current state in gasification technology, an auxilliary fuel such as dried wood chips may be needed for ash and/or moisture control where sludge/wastepaper mixtures are gasified.

2. Given a wastepaper collection percentage of 40 percent, the cost of sludge/wastepaper gasification is competitive with the cost of sludge disposal by landfilling when the cost of electricity is greater than: $0.12/kWh for communities of 10,000 persons, $0.09/kWh for communities of 30,000 persons, $0.085/kWh for communities of 50,000 persons.

3. The economic feasibility of sludge/wastepaper gasification is sensitive to the cost of electricity and wood chips, the solids content of the sludge, and the percentage of wastepaper collected.

85

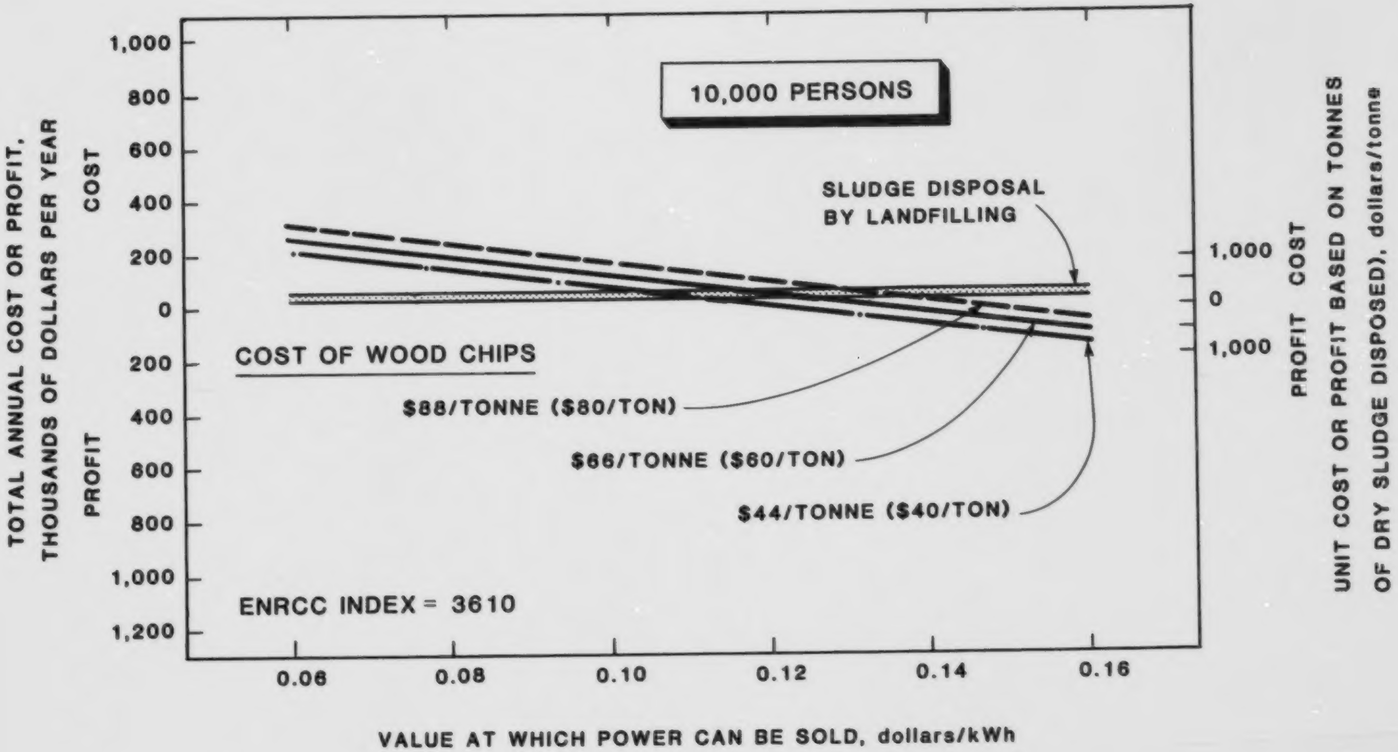


Figure 24. Sensitivity of the net total annual cost of a sludge/wastepaper gasification system to the wood chip and power costs for a communty of 10,000 persons.

16

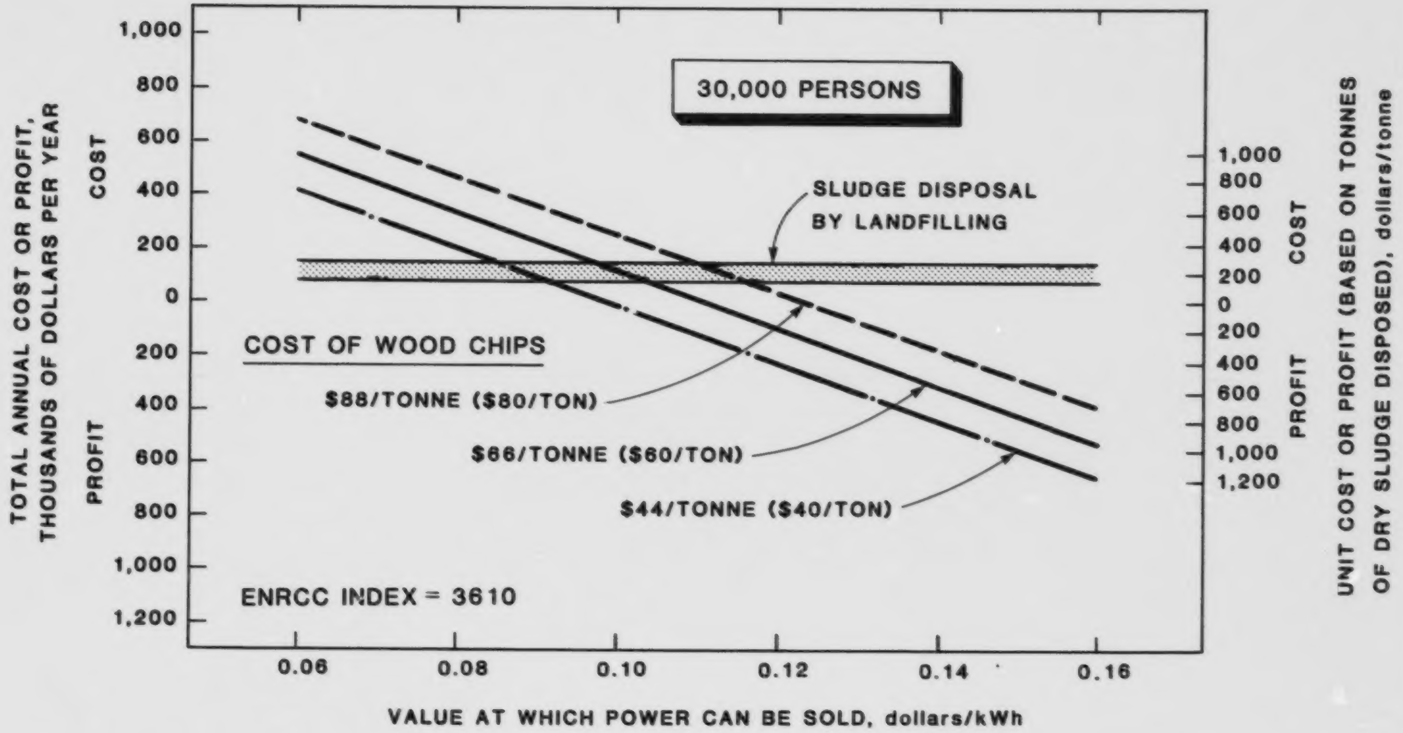


Figure 25. Sensitivity of the net total annual cost of a sludge/wastepaper gasification system to the wood chip and power costs for a community of 30,000 persons.

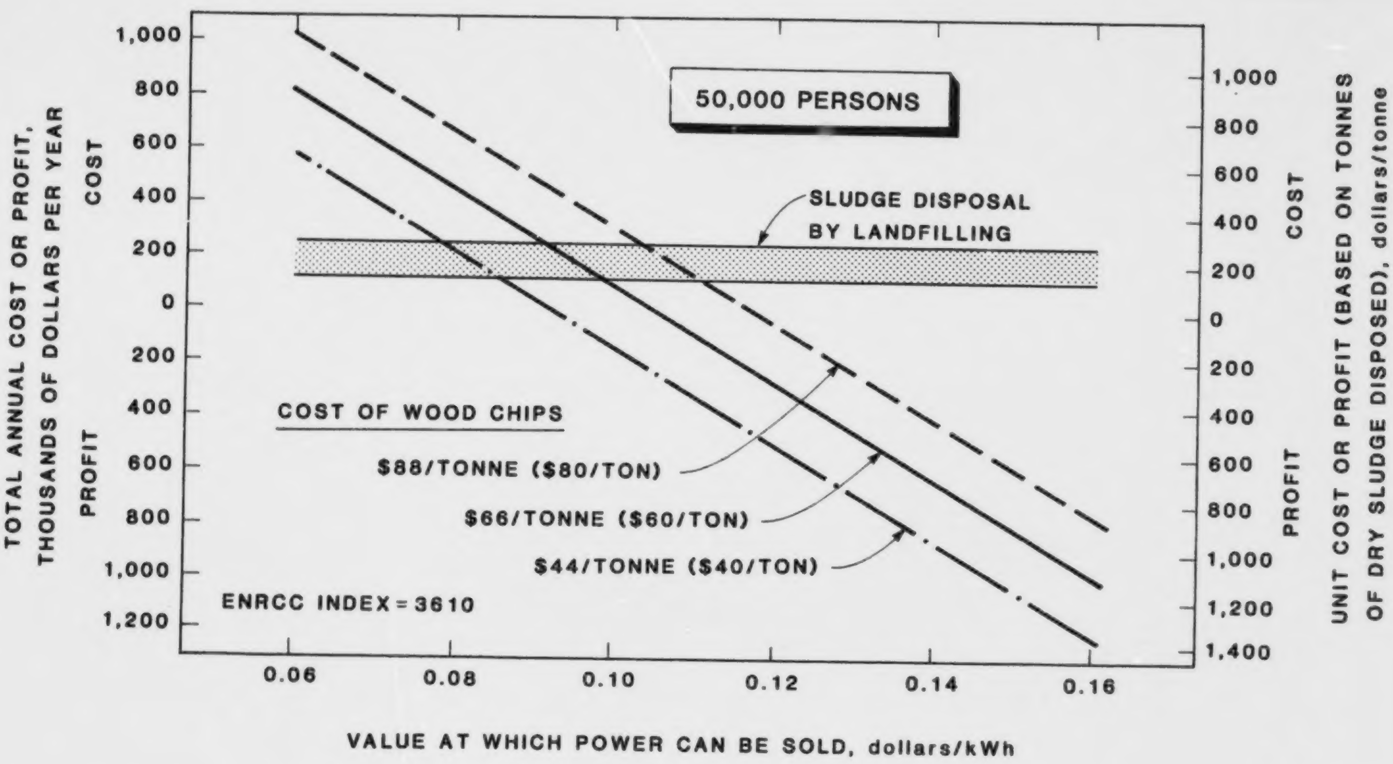


Figure 26. Sensitivity of the net total annual cost of a sludge/wastepaper gasification system to the wood chip and power costs for a community of 50,000 persons.

REFERENCES

1. ASAE Standard: ASAE S269.2 - Wafers, Pellets and Crumbles-Definitions and Methods for Determining Specific Weight, Durability and Moisture Content. In: 1977 Agricultural Engineers Yearbook. American Society of Agricultural Engineers, St. Joseph, Michigan, 1977.

2. Aurs-Andritz Inc., (written estimate for model CPF 40 SM), Creek, J., Arlington, Texas, March 10, 1981.

3. Baldwin, R., T. Barnett, R. Richards, and J. Price. Codisposal of Municipal Solid Waste and Sewer Sludge: An Analysis of Constraints. EPA Report SW-184 C, 1980.

4. Bartley, D.A. Investigation of the Economic Feasibility of Disposal of Sewage Sludge by Co-Gasification with Source Separated Wastepaper. MS Thesis, University of California, Davis, 1980.

5. Bosch, H., G.J. Kleerebezem, and P. Mars. Activated Carbon from Activated Sludge. Journal of the Water Pollution Control Federation, 48:551, 1976.

6. Bowen, N.L., J.F. Schairer, and E. Posnjak. The System, CaO-FeO-SiO_2. American Journal of Sciences, 5th Series, 26:204, 1933.

7. Burdick, M.D. Studies on the System Lime-Ferric Oxide-Silica. Journal of Research for the National Bureau of Standards, 25:476, 1940.

8. Chemical Engineers Handbook, 5th Edition. R.H. Perry and C.H. Chilton, editors. McGraw-Hill, 1973.

9. Cruz, I.E. Producer Gas from Agricultural Wastes - Its Production and Utilization in a Converted Oil-Fired Boiler. Resource Recovery and Conservation, 2(1976/1977), pp. 241-256, Elsevier Scientific Publishing Company, Amsterdam, 1976.

10. Culp, R.L., G.M. Wesner, and G.L. Culp. Advanced Wastewater Treatment, 2nd ed. Van Norstrand Reinhold, New York, 1978.

11. Culp, G.L. and A.J. Schuckrow. What Lies Ahead for PAC?. Water and Wastes Engineering. Technical Publishing Co., New York, February, 1977.

12. Davis, D.A., S.A. Vigil, and G. Tchobanoglous. Evaluation of Residual Char from the Gasification of Solid Wastes as a Substitute for Powdered activated Carbon. Presented at the 3rd Symposium on Biotechnology in Energy Production and Conservation, Gatlinburg, Tennessee, May 14, 1981.

13. Davis Waste Removal Co., (personal communication), Davis, Ca., September, 1981.

14. Decision-Makers Guide in Solid Waste Management. EPA Report SW-500, 1976.

15. Emission Testing of University of California, Davis Sludge Gasifier. Unpublished report submitted to U.S. EPA Environmental Science Research Laboratory, Research Triangle Park, by Engineering-Science, 125 West Huntington Drive, Arcadia, CA, Task Order 16, Contract 68-01-6312, September, 1981.

16. Eggen, A.C.W., and R. Kraatz. Gasification of Solid Wastes in Fixed Beds. ASME Paper 74-WA/Pwr-10. Presented at the Winter Annual Meeting, American Society of Mechanical Engineering, New York City, November 1974.

17. Goss, J.R., Interim Report - Pilot Plant Gasification Tests. Department of Agricultural Engineering, University of California, Davis, January 1979.

18. Graham, R. and D.P.C. Fung. A Review of Biomass Gasification -The Role of Catalysts. Report OPX22IE, Eastern Forest Products Laboratory, Ottawa, Ontario, Canada, 1979.

19. Gumz, W. Gas Producers and Blast Furnaces - Theory and Methods of Calculation. John Wiley and Sons, Inc., New York, 1950.

20. Herning, F., and L. Zipperer. Gas-u Wasserfach, 79(49):69, 1936.

21. Hoffman, E.J. Coal Conversion. The Energon Co., Laramie, Wyoming, 1978.

22. Inbert Energietechnik GmbH, (personal communication with W.O. Zerbin), Bonner Strasse 49, 5354 Weilerwist, West Germany, March 1982.

23. International Harvester Dealer, (personal communication) West Sacramento, Ca., September, 1981.

24. JANAF Thermochemical Tables. Clearinghouse for Federal Scientific and Technical Information, August, 1965.

25. Jantunen, M., and D. Asplund. Peat Gasification Experiments and the Use of Gas in a Diesel Engine. Technical Research Center of Finland, Fuel and Lubricant Research Laboratory, Espoo, Finland, 1979.

26. Jenkins, B. Downdraft Gasification Characteristics of Major California Residue-Derived Fuels. Ph.D. Thesis, University of California, Davis, 1980.

27. Jones, J.L. Converting Solid Wastes and Residues to Fuel. Chemical Engineering, McGraw-Hill Inc., New York, pp. 87-94, January 2, 1978.

28. Jones, J.L., R.C. Phillips, S. Takaoka, and F.M. Lewis. Pyrolysis, Thermal Gasification, and Liquefaction of Solid Wastes and Residues - Worldwide Status of Processes. Presented at the ASME 8th Biennial National Waste Processing Conference, Chicago, May 1978.

90

29. Kaupp, A., (personal communication), Department of Agricultural Engineering, University of California, Davis, March 1982.

30. Kaupp, A. and J.R. Goss. State of the Art for Small Scale (to 50 kW) Gas Producer - Engine Systems. Final Report, U.S. Department of Ag., Forest Service Contract No. 53-319R-0-141, March 1981.

31. Kjellstrom, B. Producer Gas 1980, Local Electricity Generation from Wood and Agricultural Residues. The Beiger Institute, The Royal Swedish Academy of Sciences, Stockholm, Sweden, June 1981.

32. Lamorey, G. Mass and Energy Balances for a Fluidized Bed Gasifier Fueled with Almond Shell Screenings. M.S. Thesis, University of California, Davis, March 1983.

33. Lewis, F.M. Thermodynamic Fundamentals for the Pyrolysis of Refuse. In Proceedings 1976 National Waste Processing Conference, Boston, May 23-26, 1976, American Society of Mechanical Engineers, New York, 1976.

34. Maurer, R.E., and D. Lonick. Firsthand Look at Coal Gasifiers. Instruments and Control Systems, August, 1979.

35. Metcalf and Eddy, Inc. Wastewater Engineering: Treatment Disposal and Reuse, 2nd ed. McGraw-Hill Book Co., New York, 1979.

36. Moteurs Duvant, B.P. 599, F. 59308 Valenciennes, France.

37. Nelson, G.B. Stable Blocks Formed on Shredded Paper-Like Materials. U.S. Patent No. 3,949,036, April 6, 1976.

38. Nelson, G.B., and G.C. Nelson. Briquetting of Organic Material for Feed and Fuel. Presented before the Bi-Annual Meeting of the Institute of Briquetting and Agglomeration, San Diego, 1979.

39. Nordstrom, O. Redogorelse for Riksnamndens for ekonomish forsvar sberedskap forskingsock fursosverksamhet pa gengasomradet rid statnes maskinpravnigar 1957-1963. Chapters 1-5, Obtainable from National Swedish Testing Institute for Agricultural Machinery, Box 7035, 75007 Uppsala, Sweden, (in Swedish), 1963.

40. Ortiz-Cavante, J., S.A. Vigil, J.R. Goss, and G. Tchobanoglous. Comparison of a 34 kW Diesel Engine Fueled with Low Energy Gas, Biogas, and Diesel Fuel. Presented at the 3rd Symposium on Biotechnology in Energy Production and Conservation, Gatlinburg, Tennessee, May 14, 1981.

41. Papakube Corp., (personal communication), San Diego, Ca., October, 1981.

42. Raabe, O.G. Aerosol Aerodynamic Size Conventions for Inertial Sampler Calibration. Journal of the Air Pollution Control Association, 26(9), September 1976.

43. Rambush, N.E. Modern Gas Producers. Von Norstrand Company, New York, 1923. 545 pp.

44. Reed, T.B. A Survey of Biomass Gasification, Volume II - Principles of Gasification. SERI Report No. TR-33-239, Solar Energy Research Institute, Golden, Colorado, 1979.

45. Reed, T.B. A Survey of Biomass Gasification, Volume III - Current Technology and Research. SERI Report No. TR-33-239, Solar Energy Research Institute, Golden, Colorado, April 1980.

46. Reynolds, W.C. Thermochemical Properties in SI. Department of Mechanical Engineering, Stanford University, Stanford, CA, 1979.

47. Robert Snow Means Company, Inc. Building Construction Costs Data 1981. Kingston, Mass., 1980.

48. Roberts, P.V., J.O. Leckie, and P.H. Brunner. Pyrolysis for the Production of Activated Carbon from Cellulosic Solid Wastes. In Solid Wastes and Residues -Conversion by Advanced Thermal Processes, J.L. Jones and Radding, S.B., editors. American Chemical Society, Washington, D.C., 1978.

49. Sacramento County Department of Public Works, (personal communication), Sacramento, Ca., October, 1981.

50. Sealock, L.J. Jr., S.L. Weber, and L.J. Mudge. Kinematics and Mechanisms of Steam Gasification of Biomass in the Presence of Alkali Carbonates. Biosources Digest, 2(1), 1980.

51. Separating Paper at the Waste Source for Recycling. EPA Report SW-128, 1974.

52. Serper, A. Overview - Resource Recovery Field Stands Poised Between Problems, Solutions. Solid Waste Management, 23(5):16, 1980.

53. Sigler, J.E. Activated Carbon and Fuel from Sewage Solids. In: Solid Wastes and Residues - Conversion by Advanced Thermal Processes, Jones, J.L., and S.B. Radding editors American Chemical Society, Washington, D.C., 1978.

54. Sorbo, N.W., S.A. Vigil and G. Tchobanoglous. Technical and Economic Feasibility of Small Scale Co-Gasification of Densified Sludge and Solid Waste. Presented before the Symposium on Energy from Biomass and Wastes VI, Institute of Gas Technology, Lake Buena Vista, Florida, January 25-29, 1982.

55. Stairmand, C.J. Transactions of the Institution of Chemical Engineering. 29:356, 1951.

56. Stevenson, M.K. Preparation and Evaluation of Activated Carbon Produced from Municipal Refuse. Doctor of Engineering Thesis, Stanford University, Stanford, California, 1977.

57. Standards of Performance for New Stationary Sources. Federal Register, 36(47) December, 1971.

58. Tchobanoglous, G., H. Theisen, and R. Eliassen. Solid Wastes, Engineering Principles and Management Issues. McGraw-Hill, New York, 1977.

59. Treatability Manual, Volume IV. Cost Estimating. EPA-600/8-80-042d, July, 1980.

60. Vigil, S.A. Thermal Co-Gasification of Densified Sewage and Solid Wastes. Ph.D. Thesis, University of California, Davis, 1981.

61. Vigil, S.A. and G. Tchobanoglous. Co-Gasification of Densified Sludge and Solid Waste in a Downdraft Gasifier. U.S. EPA, Final Report, Grant No. R-805-70-3010, 1981.

62. Wallace, R.N., and D.E. Burns. Factors Affecting Powdered Carbon Treatment of a Municipal Wastewater. Journal of the Water Pollution Control Federation, 48(3):511, 1976.

63. Wilke, C.R. A Viscosity Equation for Gas Mixtures. Journal of Chemical Physics, 18(4):517, 1950.

64. Williams, R.O., and J.R. Goss. An Assessment of the Gasification Characteristics of Some Agricultural and Forest Industry Residues Using a Laboratory Gasifier. Resource Recovery and Conservation, 3, pp. 317-329, 1979.

65. Williams, R.O., J.R. Goss, J.J. Mehlschau, B. Jenkins, and J. Ramming. Development of Pilot Plant Gasification Systems for the Conversion of Crop and Wood Residues to Thermal and Electrical Energy. In: Solid Wastes and Residues Conversion by Advanced Thermal Processes, J.L. Jones and S.B. Radding, Editors. ACS Symposium Series, American Chemical Society, Washington, D.C., pp. 142-162, 1978.

66. Williams, R.O., and B. Horsfied. Generation of Low-BTU Fuel Gas from Agricultural Residues - Experiments with a Laboratory Scale Gas Producer. In: Food, Fertilizer, and Agricultural Residues - Proceedings of the 1977 Cornelll Agricultural Waste Management Conference, Ann Arbor Science Publishers, Inc., Ann Arbor, 1977.

APPENDIX A

MASS AND ENERGY BALANCE COMPUTATIONS

A methodology and computer program, developed by Lamorey for fluidized bed gasifiers (32), was used to compute mass and energy balances for the sludge/wastepaper gasifier. The methodology of the mass and energy balance computations, presented below, is a summary from Lamorey's work (32). A listing of the mass and energy balance computer programs and outputs from Runs 14 through 21-B and 26 through 28-B is presented in Appendix B.

Mass Balance Measurements

The following mass balance data were recorded during operation of the gasifier:

1. The combustion air volume flowrate was obtained from the time average of the pressure drop across an orifice plate in the air inlet line to the blower. The orifice plate was calibrated by using a portable venturi meter. The air inlet pressure drop measurements were taken at 5 minute intervals.

2. The mass flow rate of the fuel was obtained by weighing the gasifier, which was mounted on platform scales, at 5 minute intervals.

3. The mass flow rate of the char was obtained by weighing the char before and after a run and dividing by the net run time. The mass flow rate of the fly ash was calculated similarly. The sum of the char rate and the fly ash rate is entered into the program as the char mass flow rate.

4. Representative fuel and char samples were taken for moisture content determination and ultimate analysis. Fuel and char composition data are summarized in Tables 3 and 4.

5. Gas composition measurements in percent volume of dry gas at ambient temperature and pressure of CO, CO_2, H_2, O_2 and THC (total hydrocarbon) were taken at 5 minute intervals. Time averages of this data are presented in Table 7.

Mass Balance Calculations

Mass balance values that were not measured were calculated by considering elemental and overall mass balances. Terms used in the mass balance calculations are described in Table A-1. The following method was used to analyze mass balance data.

Table A-1
LIST OF MASS BALANCE TERMS

Description of Term	Symbol
Volume flowrates (m^3/min)	
air volume flowrate at 298°K, 1 atm. (orifice)	$\dot{V}_a$
dry product gas volume flowrate at 298°K, 1 atm. (derived)	$\dot{V}_g$
Mass flowrates (kg/hr)	
dry fuel (measured)	$\dot{m}_f$
water from fuel moisture (measured)	$\dot{m}_m$
combustion air (orifice)	$\dot{m}_a$
dry product gas (derived)	$\dot{m}_g$
water vapor in product gas (derived)	$\dot{m}_v$
char (measured)	$\dot{m}_c$
solid particles and tars in product gas (derived)	$\dot{m}_p$
excess mass (derived)	$\dot{m}_{ex}$
Elemental mass flowrates (kg/hr)	
carbon in fuel	$\dot{m}_{fc}$
carbon in char	$\dot{m}_{cc}$
carbon in product gas	$\dot{m}_{gc}$
carbon in solid particles and tar of product gas	$\dot{m}_{pc}$
hydrogen in dry fuel	$\dot{m}_{fh}$
hydrogen from water in fuel	$\dot{m}_{mh}$
hydrogen in dry product gas	$\dot{m}_{gh}$
hydrogen from water vapor in product gas	$\dot{m}_{vh}$
oxygen in combustion air	$\dot{m}_{ao}$
oxygen in dry fuel	$\dot{m}_{fo}$
oxygen from water in fuel	$\dot{m}_{mo}$
oxygen in dry product gas	$\dot{m}_{go}$
oxygen from water vapor in product gas	$\dot{m}_{vo}$

Table A-1 (continued)

Description of Term	Symbol
Mass fractions	
kg carbon in fuel per kg dry fuel	W_{fc}
kg carbon in char per kg dry fuel	W_{cc}
kg hydrogen in fuel per kg dry fuel	W_{fh}
kg oxygen in fuel per kg dry fuel	W_{fo}
kg water in wet fuel per kg dry fuel	W_{fm}
kg water vapor in wet product gas per kg dry product gas at temperature T	W_{gv}^{T}
Product gas volume (or mole) fraction	
m^3 of species i per m^3 of product gas	x_i
Molecular weight	
kg air per kg mole air	M_a
kg dry fuel per kg mole dry fuel	M_f
kg char per kg mole char	M_c
kg dry product gas per kg mole dry product gas	M_g
kg species i per kg mole species i	M_i
Other	
universal gas constant (= 8314.5 J/kg · mole · °K)	R
temperature of product gas at gasifier exit (°K)	Te
reference temperature (= 298°K)	Tr
reference pressure (= 1 atm)	Pr

1. An overall mass balance equates mass entering the gasifier as dry fuel, fuel moisture and the combustion air to mass leaving as char, dry product gas, water vapor in the gas and particulates in the gas (Figure A-1 and Equation 1). The dry fuel and the fuel moisture are measured together as the wet fuel rate. The air mass flowrate is determined from the measured air volume flowrate and the ideal gas law by Equation 2. Determination of the char rate has been described. Elemental mass balances described below are used to determine the dry product gas rate, the amount of water vapor in the product gas and the amount of particulate matter in the product gas.

$$\dot{m}_f + \dot{m}_m + \dot{m}_a = \dot{m}_c + \dot{m}_g + \dot{m}_v + \dot{m}_p \tag{1}$$

$$\dot{m}_a = \dot{V}_a \left(\frac{Pr}{RTr}\right) M_a \tag{2}$$

2. The dry gas production rate is calculated from the nitrogen balance (Figure A-2). The volume percent nitrogen in the dry product gas is determined by summing the percent CO, CO_2, THC, and H_2, then subtracting from 100%. The volume flowrate of the product gas is calculated from the nitrogen in the air and the nitrogen in the dry product gas by Equation 3 assuming the nitrogen content of air by volume is 79%. The molecular weight of the air and the product gas have been determined assuming that 1.3% of the nitrogen present is actually argon. Nitrogen in the fuel and char is present at less than 1% and is ignored. The dry product gas mass flowrate is determined from the volume rate and the ideal gas law (Equation 4).

$$\dot{V}_g = \frac{0.79\ \dot{V}_a}{X_{N_2}} \tag{3}$$

$$\dot{m}_g = \dot{V}_g \left(\frac{Pr}{RTr}\right) M_g \tag{4}$$

3. The mass rate of the water vapor in the product gas is calculated from the mass rate of the product gas and the mass fraction of water vapor in the product gas by Equation 5. (Note: The water vapor fraction in the product gas was measured during Runs 17, 20, 21-A, 21-B, 26, 27, 28-A, and 28-B, but these values were not used to perform the mass balance). The mass fraction of the water vapor is calculated from either the oxygen or the hydrogen balances.

$$\dot{m}_v = \dot{m}_g W_{gv}^{Te} \tag{5}$$

a. The oxygen balance involves fuel rate, fuel moisture content, fuel oxygen content, air flowrate, dry gas flowrate, dry gas composition and

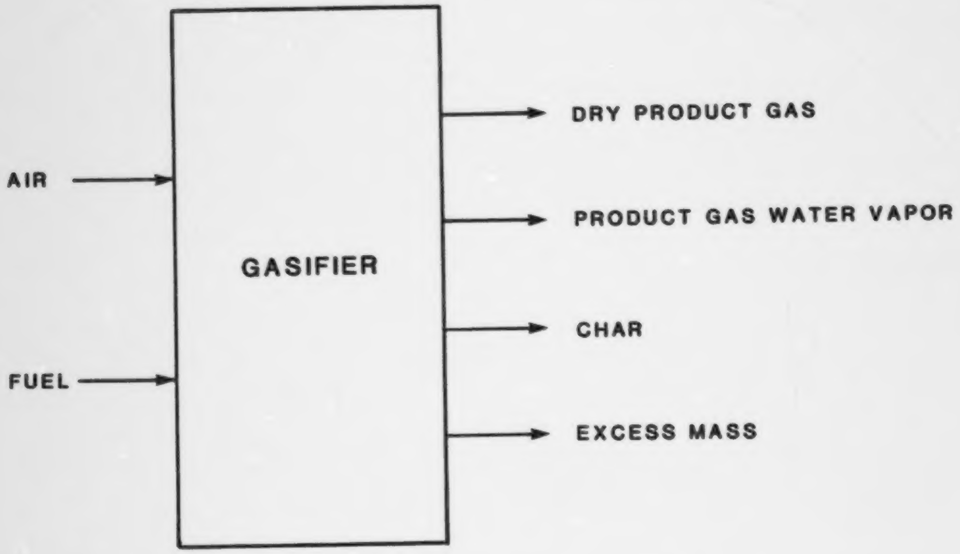

AIR
FUEL
GASIFIER
DRY PRODUCT GAS
PRODUCT GAS WATER VAPOR
CHAR
EXCESS MASS

Figure A-1. Overall mass balance.

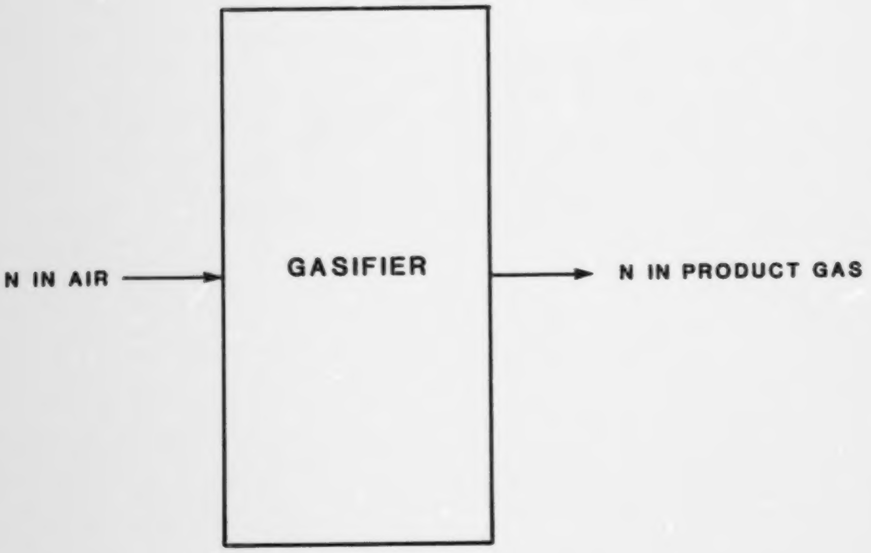

N IN AIR
GASIFIER
N IN PRODUCT GAS

Figure A-2. Nitrogen mass balance.

gas water vapor (see Figure A-3). The oxygen in the gas water vapor is calculated from the difference of the incoming oxygen in the fuel and air and the exiting oxygen in the CO and CO_2 of the gas (see Equations 6 through 10). The mass fraction of water vapor in the gas is calculated from the oxygen of the gas water vapor and the dry gas flowrate in Equation 11.

$$\dot{m}_{vo} = \dot{m}_{ao} + \dot{m}_{fo} + \dot{m}_{mo} - \dot{m}_{go} \tag{6}$$

$$\dot{m}_{ao} = 0.21\, \dot{V}_a \left(\frac{Pr}{RTr}\right) M_{O_2} \tag{7}$$

$$\dot{m}_{fo} = W_{fo}\, \dot{m}_f \tag{8}$$

$$\dot{m}_{mo} = W_{fm}\, \dot{m}_f \left(\frac{M_O}{M_{H_2O}}\right) \tag{9}$$

$$\dot{m}_{go} = \dot{V}_g \left(\frac{Pr}{RTr}\right) M_O \, (X_{CO} + 2X_{CO_2}) \tag{10}$$

$$W^{Te}_{gv} = \frac{\dot{m}_{vo}\left(\frac{M_{H_2O}}{M_O}\right)}{\dot{V}_g \left(\frac{Pr}{RTr}\right) M_g} \tag{11}$$

b. The hydrogen balance involves fuel rate, fuel moisture content, fuel hydrogen content, dry gas flowrate, dry gas composition and gas water vapor (see Figure A-4). The hydrogen in the water vapor of the gas is calculated from the difference of the incoming hydrogen in the fuel and the hydrogen exiting in the gas as THC and H_2 (see Equations 12 through 15). Hydrogen exiting as tar in the gas is neglected since no data are available on tar mass flowrate and composition. The mass fraction of water vapor in the gas is calculated from the hydrogen in the water vapor and the dry gas flowrate by Equation 16.

$$\dot{m}_{vh} = \dot{m}_{fh} + \dot{m}_{mh} - \dot{m}_{gh} \tag{12}$$

$$\dot{m}_{fh} = W_{fh}\, \dot{m}_f \tag{13}$$

$$\dot{m}_{mh} = W_{fm}\, \dot{m}_f \left(\frac{2M_H}{M_{H_2O}}\right) \tag{14}$$

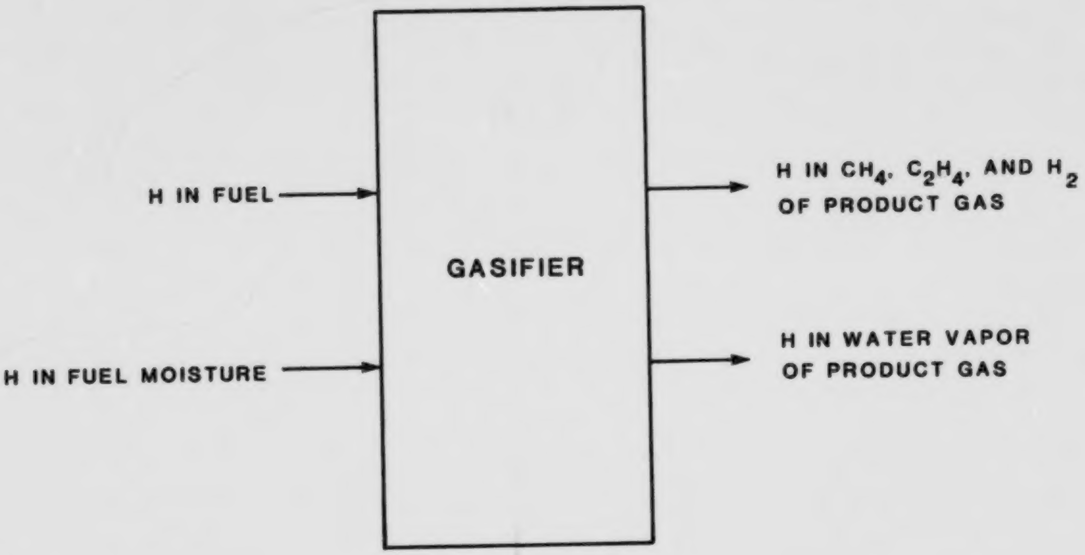

H IN FUEL
H IN FUEL MOISTURE
GASIFIER
H IN CH_4, C_2H_4, AND H_2 OF PRODUCT GAS
H IN WATER VAPOR OF PRODUCT GAS

Figure A-3. Hydrogen mass balance.

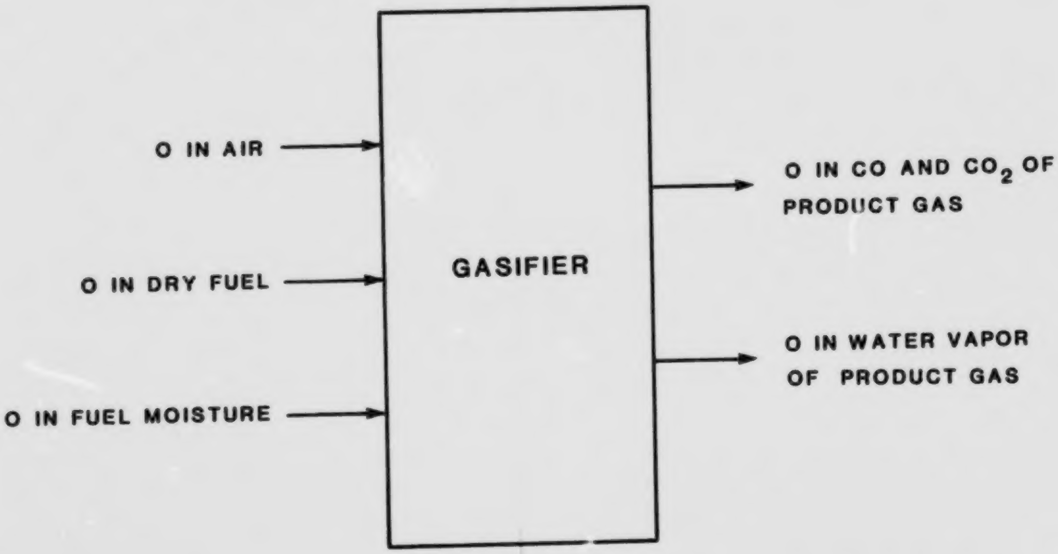

O IN AIR
O IN DRY FUEL
O IN FUEL MOISTURE
GASIFIER
O IN CO AND CO_2 OF PRODUCT GAS
O IN WATER VAPOR OF PRODUCT GAS

Figure A-4. Oxygen mass balance.

$$\dot{m}_{gh} = \dot{V}_g \left(\frac{Pr}{RTr}\right) M_H \left(4X_{CH_4} + 4X_{C_2H_4} + 2X_{H_2}\right) \tag{15}$$

$$w_{gv}^{Te} = \dot{m}_{vh} \left(\frac{M_{H_2O}}{2M_h}\right) \tag{16}$$

4. Excess carbon in the products from a carbon balance is assumed to be carbon contained in the solid particles and tars in the produce gas, not collected in the cyclone. The carbon balance involves fuel rate, fuel carbon content, char rate, char carbon content, dry gas flowrate and dry gas composition (see Figure A-5). The mass of carbon exiting in the gas as solid particles and tar is calculated as the difference of the incoming carbon in the fuel and the exiting carbon in the char and in the gas as CO, CO_2 and THC (see Equations 17 through 20). The mass of the solid particles and tars is estimated by assuming they have a carbon content equal to the char carbon content (see Equation 25).

$$\dot{m}_{pc} = \dot{m}_{fc} - \dot{m}_{cc} - \dot{m}_{gc} \tag{17}$$

$$\dot{m}_{fc} = \dot{m}_f \, W_{fc} \tag{18}$$

$$\dot{m}_{cc} = \dot{m}_c \, W_{cc} \tag{19}$$

$$\dot{m}_{gc} = \dot{V}_g \left(\frac{Pr}{RTr}\right) M_c \left(X_{CO} + X_{CO_2} + X_{CH_4} + 2X_{C_2H_4}\right) \tag{20}$$

$$\dot{m}_p = \frac{\dot{m}_{pc}}{W_{cc}} \tag{21}$$

5. The excess mass term represents the mass of the solid particles not collected in the cyclone and the tars in the product gas and is calculated using Equation 22 below. Note that the water vapor in the product gas ($\dot{m}_v$) is obtained from the product gas water vapor mass flowrate determined by the hydrogen balance.

$$\dot{m}_{ex} = \dot{m}_f + \dot{m}_f + \dot{m}_a - \dot{m}_g - \dot{m}_v - \dot{m}_c \tag{22}$$

Energy Balance Calculations

An energy balance for a steady state process equates the energy entering and exiting a control volume. For a gasifier, the major energy input is the heat of combustion of the fuel and the energy outputs include the heat of combustion and

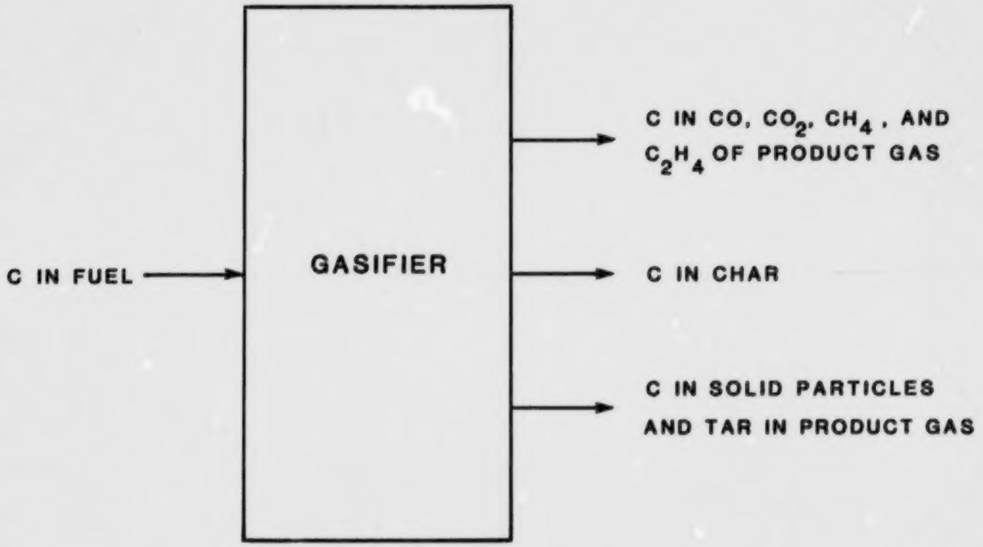

C IN FUEL
GASIFIER
C IN CO, CO$_2$, CH$_4$, AND C$_2$H$_4$ OF PRODUCT GAS
C IN CHAR
C IN SOLID PARTICLES AND TAR IN PRODUCT GAS

Figure A-5. Carbon mass balance.

sensible heat of the gas, the sensible heat and heat of combustion of the char, and convection and radiation losses. To compute a consistent energy balance, the reference state of all of the water entering or leaving must be consistent. The reference state of water here has been chosen as liquid at 25 degrees centigrade. Higher heating values of the fuel and gas are used in the energy balance since these are references to liquid water. The terms used in the energy balance calculations are described in Table A-2. The method used to analyze energy balance data is described below.

1. Energy in the fuel includes the heat of combustion of the dry fuel and the sensible heat of the fuel and the fuel moisture. Since the reference temperature and the temperature of the fuel as it enters the gasifier are approximately equal, the sensible heat of the fuel and fuel moisture are small. The heat of combustion of the fuel is determined by combusting a dry sample of the fuel in a bomb calorimeter. The bomb calorimeter measures the enthalpy at constant volume and approximately constant temperature. This differs from the desired enthalpy for gasification, an approxiamtely constant pressure process, by the flow work of moving reactants into the control volume and removing products from the control volume. This correction is given in Equation 23 and is explained in detail by Jenkins (26).

$$H_f = U_f + \frac{1}{2}\left(Z_f - \frac{Y_f}{2}\right)\frac{RTr}{M_f} \qquad (23)$$

2. The sensible and latent heat of the air blast can be calculated from the temperature and relative humidity of the air. This energy was found by Jenkins (26) to be less than 1% of the heat of combustion of the fuel and has been ignored in the energy balance computations.

3. Gas energy outputs include the heat of combustion and sensible heat of the dry gas and the sensible and latent heat of the water in the gas.

   a. The heat of combustion of the dry gas is calculated by multiplying the volume fraction of each gas species by the higher heating value of the species and summing over all species as in Equation 24. This quantity multiplied by the dry gas rate equals the chemical energy production rate.

$$E_g^H = \sum_{i=1}^{n} E_i^H X_i \qquad (24)$$

   b. The sensible heat of the dry gas and the sensible and latent heat of the water vapor in the gas, released upon cooling the gas from the gas exit temperature to the reference temperature, can be analyzed by considering an energy balance for a condenser system (Figure A-6). The energy entering the condenser is the enthalpy of the hot dry gas and the enthalpy of the hot water vapor. The energy leaving the condenser includes the enthalpy of the cool dry gas, the enthalpy of the cool water

Table A-2

LIST OF ENERGY BALANCE TERMS

Description of Term	Symbol
Enthalpies	
enthalpy of combustion of fuel at constant pressure (MJ/kg)	H_f
enthalpy of combustion at constant volume (internal energy) of fuel (MJ/kg)	U_f
enthalpy of combustion of char at constant pressure (MJ/kg)	H_c
enthalpy of combustion of constant volume (internal energy) (MJ/kg)	U_c
enthalpy of liquid water at temperature T	H_ℓ^T
enthalpy of water vapor at temperature T	H_v^T
Mole fractions	
kg mole hydrogen in fuel per kg mole fuel	Y_f
kg mole oxygen in fuel per kg mole fuel	Z_f
kg mole hydrogen in char per kg mole char	Y_c
kg mole oxygen in char per kg mole char	Z_c
Gas heating values	
higher heating value of product gas mixture (MJ/m^3)	E_g^H
higher heating value of species i (MJ/m^3)	E_i^H
lower heating value of product gas (MJ/m^3)	E_g^L
lower heating value of species i (MJ/m^3)	E_i^L
Sensible heat	
sensible heat of gas component i between temperatures T_1 and T_2 (MJ/kg)	$\Delta H_i {}_{T_2}^{T_1}$
sensible heat of dry gas mixture between temperatures T_1 and T_2 (MJ/kg)	$\Delta H_g {}_{T_2}^{T_1}$

Table A-2 (continued)

Description of Term	Symbol
Efficiency	
hot gas efficiency	η_{HG}
cold gas efficiency	η_{CG}
Other	
saturation vapor pressure at temperature T	P_v^T
heat removed by cooling wet gas (MJ/hr)	q_c
heat losses due to radiation, convection, and unaccounted quantities (MJ/hr)	q_L

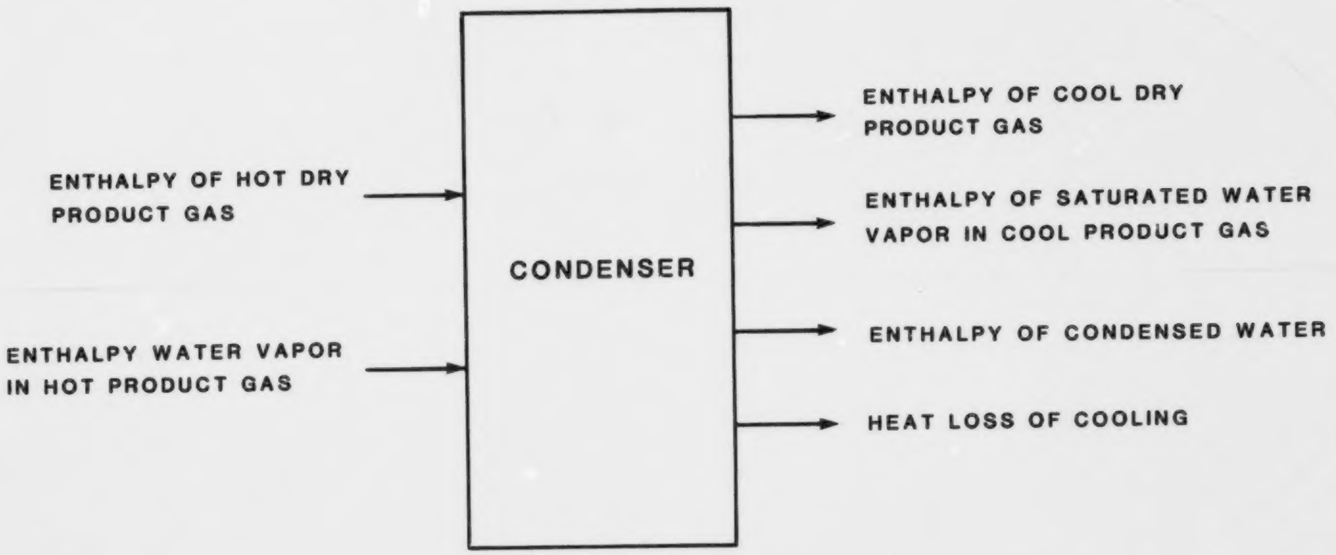

ENTHALPY OF HOT DRY PRODUCT GAS
ENTHALPY WATER VAPOR IN HOT PRODUCT GAS
CONDENSER
ENTHALPY OF COOL DRY PRODUCT GAS
ENTHALPY OF SATURATED WATER VAPOR IN COOL PRODUCT GAS
ENTHALPY OF CONDENSED WATER
HEAT LOSS OF COOLING

Figure A-6. Condenser energy balance.

vapor, the enthalpy of the condensed water, and the energy released into the environment. This energy balance is expressed in Equation 25.

$$q_c = \dot{m}_g \; \Delta H_{g_{Tr}}^{Te} + (W_{gv}^{Te} H_v^{Te} - W_{gv}^{Tr} H_v^{Tr}) -$$

$$(W_{gv}^{Te} - W_{gv}^{Tr}) H_{\ell}^{Tr} \tag{25}$$

The change in enthalpy of the dry gas between the gas exit temperature and the reference temperature is calculated from the sensible heat and volume fractions of each gas species present (see Equation 26). The sensible heat of each gas species is determined by subtracting the enthalpy of the gas species at the gas exit temperature from the enthalpy at the reference temperature. The enthalpies are determined using the JANAF thermochemical tables (24).

$$\Delta H_{g_{Tr}}^{Te} = \sum_{i=1}^{n} \Delta \; H_{i_{Tr}}^{Te} \; X_i \tag{26}$$

The enthalpy of the hot vapor is a function of the specific humidity of the hot gas which can be calculated from experimental moisture content measurement or by hydrogen or oxygen elemental balances. The hydrogen balance results have been used here to estimate the mass fraction of water vapor in the hot gas. The enthalpy of the cool vapor depends on the specific humidity of the gas leaving the condenser which is assumed to be saturated. The specific humidity of saturated water vapor is calculated from the saturated vapor pressure at the reference temperature and the molecular weight of the gas mixture by Equation 27. The saturated vapor pressure was obtained from tables compiled by Reynolds (46).

$$W_{gv}^{Tr} = \frac{P_v^{Tr}}{Pr \;-\; P_v^{Tr}} \left(\frac{M_{H_2O}}{M_g} \right) \tag{27}$$

4. The char removed from the gas by the cyclones, and the particulate matter and tars which escape the cyclones represent another energy output. The heat of combustion of the char is determined by bomb calorimeter measurements and is corrected in the same manner as for the fuel (see Equation 28).

$$H_c = U_c + \frac{1}{2} \left(Z_c - \frac{Y_c}{2} \right) \frac{RTr}{M_c} \tag{28}$$

5. Energy losses are determined by difference of the energy inputs and outputs (see Equation 29). Energy is lost to the environment by convection and radiation. The calculated losses are also a product of measurement errors and unaccounted for quantities including the heat of combustion of the particulate matter and tars in the gas, and the sensible heat of the char, particulate matter and tars.

$$q_L = \dot{m}_f H_f - \dot{m}_c H_c - \dot{V}_g E_g^H - q_c \tag{29}$$

Process Efficiency

Efficiency is defined here as the ratio of the energy in the gas products to the heating value of the fuel. The energy in the gas is partly a function of the temperature of the gas because sensible energy increases with temperature. Therefore, the efficiency of a gasifier supplying hot gas to a burner is higher than for supplying an internal combustion engine where the gas must be cooled before induction. For both burners and engines, the water produced for combusting the hydrogen and hydrocarbon gases leaves in the vapor phase. The heat of vaporization is not available to the process and so the lower heating value of the product gas is used (see Equation 30). Hot and cold gas efficiencies have been calculated by Equations 31 and 32. Hot gas efficiency is applicable to operations where the sensible heat of the gas is utilized, such as in a burner. For operations where the gas must be cooled to be utilized, such as in an internal combustion engine, the sensible heat is not used and the cold gas efficiency is appropriate.

$$E_g^L = \sum_{i=1}^{n} E_i^L X_i \tag{30}$$

$$\eta_{HG} = \frac{\dot{V}_g E_g^L + q_c}{\dot{m}_f H_f} \tag{31}$$

$$\eta_{CG} = \frac{\dot{V}_g E_g^L}{\dot{m}_f H_f} \tag{32}$$

APPENDIX B

COMPUTER PROGRAM LISTING AND OUTPUT DATA FOR THE MASS AND ENERGY BALANCES

```
C     ENERGY BALANCE FOR GASIFIER
C     WRITTEN 8-NOV-82 BY G. LAMOREY REVISED 8-FEB-83
C     *********************************************************
      DIMENSION FU(3),X(7),MW(7),JAN(161),HHVT(7),LHVT(7)
      BYTE SPEC(30),TITLE(50),DATAF(10),DATOU(10)
      REAL MG,MD,MW,CHECK,JAN,PARTG,LHV,LHVB,LHVT,LO
      DATA SPEC /'C','O',' ','C','O','2','C','H','4',
      1'C','2','H','H','2',' ','N','2',' ','O','2',' ',
      1'C',' ',' ','H',' ',' ','O',' ',' '/
      DATA MW /28.011,44.011,16.043,28.054,2.016,
      1 28.164,32.0/
      DATA JAN /
      1 0.013,0.711,1.417,2.137,2.873,3.627,4.397,5.183,
      1 5.983,6.794,7.616,8.446,9.285,10.130,10.980,11.836,
      1 12.697,13.561,14.430,15.301,16.175,17.052,17.931,
      1 0.016,0.958,1.987,3.087,4.245,5.453,6.702,7.984,
      1 9.296,10.632,11.988,13.362,14.750,16.152,17.565,
      1 18.987,20.418,21.857,23.303,24.755,26.212,27.674,
      1 29.141,
      1 0.016,0.923,1.960,3.138,4.454,5.897,7.458,9.125,
      1 10.887,12.732,14.652,16.637,18.679,20.772,22.910,
      1 25.086,27.298,29.540,31.809,34.103,36.418,38.753,
      1 41.106,
      1 0.019,1.167,2.55,4.143,5.918,7.851,9.92,12.109,
      1 14.404,16.791,19.258,21.797,24.397,27.051,29.753,
      1 32.498,35.279,38.094,40.937,43.807,46.7,49.614,
      1 52.546,
      1 0.013,0.707,1.406,2.106,2.808,3.514,4.226,
      1 4.944,5.67,6.404,7.148,7.902,8.668,9.446,10.233,
      1 11.030,11.836,12.651,13.475,14.307,15.146,15.993,
      1 16.848,
      1 0.013,0.71,1.413,2.125,2.853,3.596,4.355,5.129,
      1 5.917,6.718,7.529,8.35,9.179,10.015,10.858,11.707,
      1 12.56,13.418,14.28,15.146,16.015,16.886,17.761,
      1 0.013,0.724,1.455,2.210,2.988,3.786,4.60,
      1 5.427,6.266,7.114,7.971,8.835,9.706,10.583,11.465,
      1 12.354,13.249,14.149,15.054,15.966,16.882,17.804,
      1 18.732/
      DATA HHVT /67.637,0.0,212.8,337.23,68.317,0.0,0.0/
      DATA LHVT /67.637,0.0,191.76,316.24,57.798,0.0,0.0/
C     **************************************************************
190   TYPE *,' ENTER 0 TO ENTER DATA ON TERMINAL,'
      TYPE *,'       1 TO ENTER DATA FROM DATA FILE.'
      READ(5,*)J
      IF (J.EQ.0) GO TO 195
      TYPE *,' ENTER TITLE OF DATA FILE AS NAME.DAT'
      READ(5,10)NNCH,(DATAF(I),I=1,NNCH)
      WRITE(5,11)(DATAF(I),I=1,NNCH)
195   TYPE *,' ENTER TITLE OF OUTPUT FILE AS NAME.DAT'
      READ(5,10)NNCH,(DATOU(I),I=1,NNCH)
      WRITE(5,11)(DATOU(I),I=1,NNCH)
      IF (J.EQ.0) GO TO 510
      OPEN(UNIT=2,STATUS='OLD',FILE=DATAF)
      READ(2,10)NCH,(TITLE(I),I=1,NCH)
      READ(2,150)TEMPF
      READ(2,150)AIRV
      READ(2,150)WF
      DO 160 I=1,3
              READ(2,150)FU(I)
160           FU(I)=FU(I)/100
      READ(2,150)FMC
      READ(2,150)ENTF
      DO 170 I=1,7
              READ(2,150)X(I)
170           X(I)=X(I)/100
      READ(2,150)TEMPG
      READ(2,150)EH1
      READ(2,150)CR
      READ(2,150)CC
      READ(2,150)CE
150   FORMAT(28X,F8.3)
      CLOSE(UNIT=2)
      GO TO 180
C     ************************************************************
C     DATA IS ENTERED ON THE TERMINAL BELOW.
510   TYPE *,' ENTER TITLE(MAX 50 CHARACTERS)'
      READ(5,10)NCH,(TITLE(I),I=1,NCH)
      TYPE *,' ENTER TEMPERATURE FOR AIR AND GAS FLOW RATES (DEG K)'
      READ(5,*)TEMPF           !INPUT AIR RATE, WET GAS RATE AND GAS
      WRITE(5,38)TEMPF         !DENSITY ARE BASED ON THIS TEMPERATURE.
      TYPE *,' ENTER AIR VOLUME FLOW RATE (M3/MIN)'
      READ(5,*)AIRV
      WRITE(5,37)AIRV
      TYPE *,' ENTER WET FUEL RATE(KG/HR)'
      READ(5,*)WF
      WRITE(5,310)WF
      TYPE *,' ENTER DRY FUEL ULTIMATE ANALYSIS:'
      DO 100 I=8,10
              WRITE(5,15)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3)
              READ(5,*)FU(I-7)
              WRITE(5,20)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3),FU(I-7)
              FU(I-7)=FU(I-7)/100
 100          CONTINUE
      TYPE *,' ENTER FUEL MOISTURE CONTENT (% DRY BASIS)'
      READ(5,*)FMC
      WRITE(5,30)FMC
      TYPE *, ' ENTER ENTHALPY OF DRY FUEL (MJ/KG)'
      READ(5,*)ENTF
      WRITE(5,35)ENTF
      CHECK=0          !CHECK TO USED TO CHECK TOTAL OF GAS
      TYPE *,' '       !SPECIES VOLUME %, SHOULD EQUAL 100.
      TYPE *,' ENTER DRY GAS COMPOSITION:'
      DO 200 I=1,7
              WRITE(5,2)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3)
              READ(5,*)X(I)
              WRITE(5,12)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3),X(I)
              CHECK=CHECK+X(I)
              X(I)=X(I)/100
200           CONTINUE
      WRITE(5,120)CHECK
      TYPE *,' ENTER EXIT GAS TEMP (DEG K BETWEEN 300 AND 2500)'
      READ(5,*)TEMPG
      WRITE(5,140)TEMPG
      IF ((TEMPG.GT.2500).OR.(TEMPG.LT.300))
      1        TYPE *,' ERROR-GAS TEMPERATURE OUT OF RANGE'
      TYPE *,' ENTER ENTHALPY OF SATURATED VAPOR FOR HOT GAS (MJ/KG)'
      READ(5,*)EH1
      WRITE(5,290)EH1
      TYPE *,' ENTER CHAR PRODUCTION RATE(KG/HR)'
      READ(5,*)CR
      WRITE(5,340)CR
      TYPE *,' ENTER CHAR CARBON CONTENT(% BY WT)'
      READ(5,*)CC
      WRITE(5,332)CC
      TYPE *,' ENTER CHAR ENERGY(MJ/KG)'
      READ(5,*)CE
      WRITE(5,335)CE
      TYPE *,' ENTER 0 TO RE-ENTER DATA, 1 TO CONTINUE'
      READ(5,*)ICHECK
      IF (ICHECK.EQ.0) GO TO 510
10    FORMAT(Q,50A1)
11    FORMAT(' ',10A)
38    FORMAT(' TEMPERATURE FOR FLOW RATES     ',F7.2,' DEG K')
37    FORMAT(' AIR VOLUME FLOW RATE           ',F7.2,' M3/MIN')
310   FORMAT(' WET FUEL RATE                  ',F7.2,' KG/HR')
15    FORMAT(' ENTER ',3A,' % WT')
20    FORMAT('                          ',3A,'    ',F7.3)
30    FORMAT(' FUEL MOISTURE CONTENT          ',F7.2,' % DRY BASIS')
35    FORMAT(' DRY FUEL ENTHALPY (HHV)         ',F7.3,' MJ/KG')
 2    FORMAT(' ENTER ',3A,' % VOL')
12    FORMAT('                          ',3A,'   ',F7.2)
120   FORMAT(' DRY GAS VOLUME % ADD UP TO     ',F7.2)
140   FORMAT(' GAS TEMPERATURE                ',F7.2,' DEGREES K')
290   FORMAT(' HOT GAS SAT VAPOR ENTHALPY      ',F7.3,' MJ/KG')
340   FORMAT(' CHAR MASS FLOWRATE             ',F7.2,' KG/HR')
```

```
332  FORMAT(' CHAR CARBON CONTENT           ',F7.2,' % WT')
335  FORMAT(' CHAR ENTHALPY (HHV)           ',F7.3,' MJ/KG')
C    ************************************************************
C    DATA PROCESSING STARTS HERE. LOWG AND PARTG ARE USED FOR INTERPOLATION
180  LOWG=INT(TEMPG/100)      !OF JANAF TABLES. LOWG CONTAINS GAS TEMP
     PARTG=TEMPG-LOWG*100     !TRUNCATED TO HUNDREDS, PARTG CONTAINS TENS
     ENTG=0                   !AND ONES PLACE DIGITS OF GAS TEMP.
     HHV=0                    !ENTG IS GAS ENTHALPY, HHV IS GAS HIGHER
     LHV=0                    !HEATING VALUE, LHV IS GAS LOWER HEATING
     MD=0                     !VALUE, MD IS MOLECULAR WEIGHT OF DRY GAS,
     MWW=0                    !MWW IS MOLECULAR WEIGHT OF WET GAS.
     DO 135 I=0,6
           ENTG=ENTG+(PARTG*(JAN(LOWG-1+(I*23))-JAN(LOWG-2+(I*23)))/100+
     1     JAN(LOWG-2+(I*23)))*X(I+1)      !IN KCAL/G MOLE.
           HHV=HHV+HHVT(I+1)*X(I+1)        !IN KCAL/G MOLE.
           LHV=LHV+LHVT(I+1)*X(I+1)        !IN KCAL/G MOLE.
135        MD=MD+X(I+1)*MW(I+1)
     ENTG=ENTG*4.1855/MD                   !IN MJ/KG.
     DD=MD/(0.08206*TEMPF)   !DRY GAS DENSITY IN KG/M3.
     HHV=HHV*DD*4.1855/MD                  !IN MJ/M3.
     LHV=LHV*DD*4.1855/MD                  !IN MJ/M3.
     HHVB=HHV*26.839                       !IN BTU/FT3.
     LHVB=LHV*26.839                       !IN BTU/FT3.
C    ****************************************************************
     FUT=FU(1)+FU(2)+FU(3)   !CALCULATION OF CONSTANT PRESSURE
     FCC=FUT*.72/FU(1)       !FUEL ENTHAPLY, ENTFP, REQUIRES CALCULATION
     FUH=FU(2)*100*FCC/FUT   !OF H AND O COEFFICIENTS, FUH AND FUO,
     FUO=FU(3)*6.25*FCC/FUT  !AND FUEL MOLECULAR WEIGHT FMW BASED
     FMW=72+FUH+16*FUO       !ON 6 MOLES C.
     ENTFP=ENTF+1.239*(FUO-FUH/2)/FMW
     FMC=FMC/100             !CONVERT PERCENT MOISTURE TO FRACTION.
     AIRM=AIRV*21170/TEMPF   !AIRM IS AIR MASS FLOWRATE.
     DGFV=.79*AIRV/X(6)      !DGFV IS DRY GAS VOLUME FLOWRATE.
     DGFM=DGFV*731.0*MD/TEMPF !DGFM IS DRY GAS MASS FLOWRATE.
     AQOM=(AIRV*4912./TEMPF+FMC*WF*(1-FMC)   !AQOM IS GAS MOISTURE
     1 *.889+FU(3)*WF*(1-FMC)-DGFV*11695.    !MASS FLOWRATE FROM
     1 *(X(1)+2*X(2))/TEMPF)*1.125           !O BALANCE. AQOP IS GAS
     AQOP=AQOM/DGFM                    !MOISTURE WT % FROM O BALANCE.
     AQHM=(FU(2)*WF*(1-FMC)+FMC*WF*(1-FMC)   !AQHM IS GAS MOISTURE
     1 *.111-DGFV*730.9*(4*X(3)+             !MASS FLOWRATE FROM
     1 4*X(4)+2*X(5))/TEMPF)*9               !H BALANCE. AQHP IS GAS
     AQHP=AQHM/DGFM                          !MOISTURE WT % FROM H BALANCE.
     EXC=FU(1)*WF*(1-FMC)-DGFV*8772.         !EXC IS EXCESS CARBON
     1 *(X(1)+X(2)+X(3)+2*X(4))/TEMPF-CR*CC/100      !FROM C BALANCE.
     EXM=WF+AIRM-DGFM-AQHM-CR !EXM IS EXCESS MASS FROM OVERALL BALANCE.
     W2=(0.03226)*18.02/MD             !W2 IS KG H2O/KG DRY GAS AT T2.
     QC=DGFM*(ENTG+(AQHP*EH1-W2*2.546) !QC IS HEAT REMOVED BY COOLING
     1 -((AQHP-W2)*1.033))   !GAS FROM GAS EXIT TEMPERATURE TO 298K.
     EGH=DGFV*HHV*60 !ECH IS CHEMICAL ENERGY OF GAS IN MJ/HR USING HHV.
```

```
      EGL=DGFV*LHV*60 !ECL IS CHEMICAL ENERGY OF GAS IN MJ/HR USING LHV.
C     ****************************************************************
      IF (FU(2)-(FU(3)/8).LE.0) BW=FU(2)*9    !BW IS BOUND WATER %, WITH
      IF (FU(2)-(FU(3)/8).GT.0) BW=FU(3)*1.125!H IN EXCESS OR LIMITING.
      EFL=WF*BW*(1-FMC)*2.257 !EFL IS LATENT HEAT IN BOUND WATER.
      EFM=WF*FMC*2.257        !EFM IS LATENT HEAT OF FUEL MOISTURE CONTENT.
      EFG=WF*(1-FMC)*ENTFP    !EFG IS GROSS ENERGY IN DRY FUEL(MJ/HR).
      EFN=EFG-EFL-EFM         !EFN IS NET ENERGY IN DRY FUEL(MJ/HR).
      ECH=CE*CR               !ECH IS ENERGY IN CHAR(MJ/HR).
      LO=EFG-EGH-QC-ECH       !LO IS ENERGY LOSSES(MJ/HR).
      PC=(EGH/EFG)*100        !PC IS CHEMICAL ENERGY IN GAS(%).
      PS=(QC/EFG)*100         !PS IS SENSIBLE ENERGY IN GAS(%).
      PCH=(ECH/EFG)*100       !PCH IS ENERGY OUT IN CHAR(%).
      PL=(LO/EFG)*100         !PL IS ENERGY LOSSES(%).
      HGO=EGL+QC              !XX IS HOT GAS OUTPUT(MJ/HR).
      HG=(HGO/EFG)*100        !HG IS HOT GAS EFFICIENCY.
      CG=(EGL/EFG)*100        !CG IS COLD GAS EFFICIENCY.
      AA=11.53*FU(1)+34.34*   !AA IS STOICH AIR KG AIR/KG DRY FUEL.
     1  (FU(2)-(FU(3)/8))
      AS=AA*WF*(1-FMC)*TEMPF*4.7225E-5        !AS IS STOICH AIR M3/MIN.
      AR=(AIRV/AS)*100                  !AR IS GASIFICATION AIR/STOICH AIR.
C*********************************************************************
C     OUTPUT TO DISKFILE.
      OPEN(UNIT=2,STATUS='NEW',FILE=DATOU)
      WRITE(2,22)(TITLE(I),I=1,NCH)
      WRITE(2,25)
      WRITE(2,38)TEMPF
      WRITE(2,37)AIRV
      WRITE(2,310)WF
      WRITE(2,39)
      DO 400 I=8,10
400         WRITE(2,20)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3),FU(I-7)*100
      WRITE(2,30)FMC*100
      WRITE(2,35)ENTF
      WRITE(2,41)
      DO 450 I=1,7
450         WRITE(2,12)SPEC(I*3-2),SPEC(I*3-1),SPEC(I*3),X(I)*100
      WRITE(2,140)TEMPG
      WRITE(2,290)EH1
      WRITE(2,340)CR
      WRITE(2,332)CC
      WRITE(2,335)CE
      WRITE(2,26)
      WRITE(2,350)AIRM
      WRITE(2,330)DGFV
      WRITE(2,355)DGFM
      WRITE(2,360)AQOP*100
      WRITE(2,275)AQOM
      WRITE(2,365)AQHP*100
      WRITE(2,280)AQHM
      WRITE(2,465)EXC
      WRITE(2,470)EXM
      WRITE(2,27)
      WRITE(2,40)HHV,HHVB
      WRITE(2,45)LHV,LHVB
      WRITE(2,50)MD
      WRITE(2,55)DD
      WRITE(2,60)ENTG
      WRITE(2,70)EFL
      WRITE(2,72)EFM
      WRITE(2,75)EFG
      WRITE(2,77)EFN
      WRITE(2,80)ECH,PCH
      WRITE(2,95)QC,PS
      WRITE(2,105)EGH,PC
      WRITE(2,110)LO,PL
      WRITE(2,115)HGO
      WRITE(2,116)EGH
      WRITE(2,122)HG
      WRITE(2,123)CG
      WRITE(2,130)AR
      WRITE(2,125)AA
      WRITE(2,126)AS
      DO 460 I=1,9
460         WRITE(2,24)
      CLOSE(UNIT=2)
      TYPE *,' ENTER 0 TO STOP, 1 TO CONTINUE.'
      READ(5,*)J
      IF (J.EQ.1) GO TO 190
22    FORMAT(' ',50A1)
24    FORMAT(' ')
25    FORMAT(' INPUT DATA:')
26    FORMAT(' OUTPUT DATA FOR MASS BALANCE:')
27    FORMAT(' OUTPUT DATA FOR ENERGY BALANCE:')
39    FORMAT(' DRY FUEL ULTIMATE ANALYSIS (% WT):')
41    FORMAT(' DRY GAS COMPOSITION (% VOL):')
330   FORMAT(' DRY GAS VOLUME FLOWRATE         ',F7.2,' M3/MIN')
360   FORMAT(' GAS WATER VAPOR MASS FRACTION   ',F7.2,
      1 ' % DRY BASIS BY O BAL')
275   FORMAT(' GAS WATER VAPOR MASS FLOWRATE   ',F7.2,
      1 ' KG/HR BY O BAL')
365   FORMAT(' GAS WATER VAPOR MASS FRACTION   ',F7.2,
      1 ' % DRY BASIS BY H BAL')
280   FORMAT(' GAS WATER VAPOR MASS FLOWRATE   ',F7.2,
      1 ' KG/HR BY H BAL')
350   FORMAT(' AIR MASS FLOWRATE               ',F7.2,' KG/HR')
355   FORMAT(' DRY GAS MASS FLOWRATE           ',F7.2,' KG/HR')
465   FORMAT(' EXCESS CARBON BY C BAL          ',F7.2,' KG/HR')
```

```
470  FORMAT(' EXCESS MASS BY MASS BAL        ',F7.2,' KG/HR')
40   FORMAT(' HHV AT 298 K                   ',F7.3,' MJ/M3      ',
     1 F7.2,' BTU/FT3')
45   FORMAT(' LHV AT 298 K                   ',F7.3,' MJ/M3      ',
     1 F7.2,' BTU/FT3')
50   FORMAT(' MOLEC. WT.-DRY GAS             ',F7.3)
55   FORMAT(' DENSITY- DRY GAS               ',F7.3,' KG/M3')
60   FORMAT(' DRY GAS SENSIBLE HEAT          ',F7.3,' MJ/KG')
70   FORMAT(' FUEL LATENT HEAT-BOUND WATER   ',F7.2,' MJ/HR')
72   FORMAT('                  FREE MOISTURE ',F7.2,' MJ/HR')
75   FORMAT(' DRY FUEL ENERGY-HHV            ',F7.2,' MJ/HR')
77   FORMAT('                 LHV            ',F7.2,' MJ/HR')
80   FORMAT(' ENERGY IN CHAR                 ',F7.2,' MJ/HR      ',
     1 F7.2,' %')
95   FORMAT(' SENSIBLE ENERGY IN GAS         ',F7.2,' MJ/HR      ',
     1 F7.2,' %')
105  FORMAT(' CHEMICAL ENERGY IN GAS         ',F7.2,' MJ/HR      ',
     1 F7.2,' %')
110  FORMAT(' ENERGY LOSSES                  ',F7.2,' MJ/HR      ',
     1 F7.2,' %')
115  FORMAT(' GAS ENERGY             HOT GAS ',F7.2,' MJ/HR')
116  FORMAT('                       COLD GAS ',F7.2,' MJ/HR')
122  FORMAT(' EFFICIENCY             HOT GAS ',F7.2,' %')
123  FORMAT('                       COLD GAS ',F7.2,' %')
130  FORMAT(' % STOICH AIR                   ',F7.2,' %')
125  FORMAT(' STOICH AIR          MASS BASIS ',F7.2,' KG/KG FUEL')
126  FORMAT('                   VOLUME BASIS ',F7.2,' M3/MIN')
     END
```

```
C.E. GASIFIER RUN 14
INPUT DATA:
TEMPERATURE FOR FLOW RATES       293.16 DEG K
AIR VOLUME FLOW RATE               0.56 M3/MIN
WET FUEL RATE                     33.20 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C        47.190
                         H         5.960
                         O        45.720
FUEL MOISTURE CONTENT             10.40 % DRY BASIS
DRY FUEL ENTHALPY (HHV)           19.420 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO       21.50
                         CO2      11.60
                         CH4       3.29
                         C2H       1.41
                         H2       16.10
                         N2       46.10
                         O2        0.00
GAS TEMPERATURE                  520.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY         2.970 MJ/KG
CHAR MASS FLOWRATE                 3.60 KG/HR
CHAR CARBON CONTENT               70.93 % WT
CHAR ENTHALPY (HHV)               25.310 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                 40.44 KG/HR
DRY GAS VOLUME FLOWRATE            0.96 M3/MIN
DRY GAS MASS FLOWRATE             60.68 KG/HR
GAS WATER VAPOR MASS FRACTION     15.98 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE      9.70 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION     13.29 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE      8.07 KG/HR BY H BAL
EXCESS CARBON BY C BAL             0.23 KG/HR
EXCESS MASS BY MASS BAL            1.29 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                       6.489 MJ/M3     174.16 BTU/FT3
LHV AT 298 K                       6.023 MJ/M3     161.64 BTU/FT3
MOLEC. WT.-DRY GAS                25.359
DENSITY- DRY GAS                   1.054 KG/M3
DRY GAS SENSIBLE HEAT              0.276 MJ/KG
FUEL LATENT HEAT-BOUND WATER      34.53 MJ/HR
                 FREE MOISTURE     7.79 MJ/HR
DRY FUEL ENERGY-HHV              577.65 MJ/HR
                LHV              535.32 MJ/HR
ENERGY IN CHAR                    91.12 MJ/HR       15.77 %
SENSIBLE ENERGY IN GAS            30.25 MJ/HR        5.24 %
CHEMICAL ENERGY IN GAS           373.64 MJ/HR       64.68 %
ENERGY LOSSES                     82.65 MJ/HR       14.31 %
GAS ENERGY             HOT GAS   377.02 MJ/HR
                      COLD GAS   373.64 MJ/HR
EFFICIENCY             HOT GAS    65.27 %
                      COLD GAS    60.03 %
% STOICH AIR                      24.61 %
STOICH AIR          MASS BASIS     5.53 KG/KG FUEL
                  VOLUME BASIS     2.28 M3/MIN
```

```
C.E. GASIFIER RUN 15
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.67 M3/MIN
WET FUEL RATE                    39.90 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       47.190
                         H        5.960
                         O       45.720
FUEL MOISTURE CONTENT             9.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          19.420 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      23.30
                         CO2     10.30
                         CH4      0.95
                         C2H      0.41
                         H2      16.00
                         N2      48.90
                         O2       0.00
GAS TEMPERATURE                 502.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        2.930 MJ/KG
CHAR MASS FLOWRATE                4.50 KG/HR
CHAR CARBON CONTENT              73.29 % WT
CHAR ENTHALPY (HHV)              26.190 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                48.38 KG/HR
DRY GAS VOLUME FLOWRATE           1.08 M3/MIN
DRY GAS MASS FLOWRATE            68.61 KG/HR
GAS WATER VAPOR MASS FRACTION    19.41 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    13.32 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    19.99 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    13.71 KG/HR BY H BAL
EXCESS CARBON BY C BAL            2.27 KG/HR
EXCESS MASS BY MASS BAL           1.46 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.236 MJ/M3     140.53 BTU/FT3
LHV AT 298 K                      4.893 MJ/M3     131.33 BTU/FT3
MOLEC. WT.-DRY GAS               25.422
DENSITY- DRY GAS                  1.057 KG/M3
DRY GAS SENSIBLE HEAT             0.246 MJ/KG
FUEL LATENT HEAT-BOUND WATER     41.87 MJ/HR
                 FREE MOISTURE    8.65 MJ/HR
DRY FUEL ENERGY-HHV             700.42 MJ/HR
                LHV             649.90 MJ/HR
ENERGY IN CHAR                  117.86 MJ/HR       16.83 %
SENSIBLE ENERGY IN GAS           40.53 MJ/HR        5.79 %
CHEMICAL ENERGY IN GAS          340.05 MJ/HR       48.55 %
ENERGY LOSSES                   201.98 MJ/HR       28.84 %
GAS ENERGY             HOT GAS  358.33 MJ/HR
                      COLD GAS  340.05 MJ/HR
EFFICIENCY             HOT GAS   51.16 %
                      COLD GAS   45.37 %
% STOICH AIR                     24.28 %
STOICH AIR          MASS BASIS    5.53 KG/KG FUEL
                  VOLUME BASIS    2.76 M3/MIN
```

```
C.E. GASIFIER RUN 16
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.71 M3/MIN
WET FUEL RATE                    42.80 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                          C      47.190
                          H       5.960
                          O      45.720
FUEL MOISTURE CONTENT            10.40 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          19.420 MJ/KG
DRY GAS COMPOSITION (% VOL):
                          CO     21.50
                          CO2    12.00
                          CH4     2.52
                          C2H     1.08
                          H2     15.50
                          N2     47.40
                          O2      0.00
GAS TEMPERATURE                 522.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        2.970 MJ/KG
CHAR MASS FLOWRATE                4.50 KG/HR
CHAR CARBON CONTENT              86.62 % WT
CHAR ENTHALPY (HHV)              30.440 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                51.27 KG/HR
DRY GAS VOLUME FLOWRATE           1.18 M3/MIN
DRY GAS MASS FLOWRATE            75.75 KG/HR
GAS WATER VAPOR MASS FRACTION    17.07 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    12.93 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    16.50 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    12.50 KG/HR BY H BAL
EXCESS CARBON BY C BAL            0.68 KG/HR
EXCESS MASS BY MASS BAL           1.32 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.939 MJ/M3     159.40 BTU/FT3
LHV AT 298 K                      5.524 MJ/M3     148.25 BTU/FT3
MOLEC. WT.-DRY GAS               25.673
DENSITY- DRY GAS                  1.067 KG/M3
DRY GAS SENSIBLE HEAT             0.274 MJ/KG
FUEL LATENT HEAT-BOUND WATER     44.52 MJ/HR
                 FREE MOISTURE   10.05 MJ/HR
DRY FUEL ENERGY-HHV             744.67 MJ/HR
                LHV             690.11 MJ/HR
ENERGY IN CHAR                  136.98 MJ/HR       18.39 %
SENSIBLE ENERGY IN GAS           42.36 MJ/HR        5.69 %
CHEMICAL ENERGY IN GAS          421.68 MJ/HR       56.63 %
ENERGY LOSSES                   143.66 MJ/HR       19.29 %
GAS ENERGY              HOT GAS 434.54 MJ/HR
                       COLD GAS 421.68 MJ/HR
EFFICIENCY              HOT GAS  58.35 %
                       COLD GAS  52.67 %
% STOICH AIR                     24.20 %
STOICH AIR           MASS BASIS   5.53 KG/KG FUEL
                   VOLUME BASIS   2.93 M3/MIN
```

```
C.E. GASIFIER RUN 17
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.48 M3/MIN
WET FUEL RATE                    22.70 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       45.020
                         H        5.620
                         O       44.140
FUEL MOISTURE CONTENT            11.20 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.730 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.10
                         CO2     11.20
                         CH4      1.62
                         C2H      0.70
                         H2      14.60
                         N2      49.90
                         O2       0.00
GAS TEMPERATURE                 522.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        2.970 MJ/KG
CHAR MASS FLOWRATE                1.60 KG/HR
CHAR CARBON CONTENT              70.53 % WT
CHAR ENTHALPY (HHV)              24.620 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                34.66 KG/HR
DRY GAS VOLUME FLOWRATE           0.76 M3/MIN
DRY GAS MASS FLOWRATE            49.12 KG/HR
GAS WATER VAPOR MASS FRACTION    12.50 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     6.14 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    11.99 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE     5.89 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -0.31 KG/HR
EXCESS MASS BY MASS BAL           0.75 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.347 MJ/M3     143.50 BTU/FT3
LHV AT 298 K                      4.994 MJ/M3     134.05 BTU/FT3
MOLEC. WT.-DRY GAS               25.924
DENSITY- DRY GAS                  1.078 KG/M3
DRY GAS SENSIBLE HEAT             0.269 MJ/KG
FUEL LATENT HEAT-BOUND WATER     22.59 MJ/HR
                 FREE MOISTURE    5.74 MJ/HR
DRY FUEL ENERGY-HHV             377.54 MJ/HR
                LHV             349.21 MJ/HR
ENERGY IN CHAR                   39.39 MJ/HR       10.43 %
SENSIBLE ENERGY IN GAS           22.95 MJ/HR        6.08 %
CHEMICAL ENERGY IN GAS          243.78 MJ/HR       64.57 %
ENERGY LOSSES                    71.42 MJ/HR       18.92 %
GAS ENERGY              HOT GAS 250.67 MJ/HR
                       COLD GAS 243.78 MJ/HR
EFFICIENCY              HOT GAS  66.40 %
                       COLD GAS  60.32 %
% STOICH AIR                     32.91 %
STOICH AIR           MASS BASIS   5.23 KG/KG FUEL
                   VOLUME BASIS   1.46 M3/MIN
```

```
C.E. GASIFIER RUN 18
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.63 M3/MIN
WET FUEL RATE                    35.20 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       45.290
                         H        5.720
                         O       43.840
FUEL MOISTURE CONTENT            12.90 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.870 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.70
                         CO2     10.90
                         CH4      1.12
                         C2H      0.48
                         H2      15.20
                         N2      49.60
                         O2       0.00
GAS TEMPERATURE                 598.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.120 MJ/KG
CHAR MASS FLOWRATE                3.10 KG/HR
CHAR CARBON CONTENT              71.97 % WT
CHAR ENTHALPY (HHV)              25.500 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                45.49 KG/HR
DRY GAS VOLUME FLOWRATE           1.00 M3/MIN
DRY GAS MASS FLOWRATE            64.42 KG/HR
GAS WATER VAPOR MASS FRACTION    16.94 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    10.91 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    17.77 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    11.45 KG/HR BY H BAL
EXCESS CARBON BY C BAL            0.94 KG/HR
EXCESS MASS BY MASS BAL           1.73 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.174 MJ/M3     138.87 BTU/FT3
LHV AT 298 K                      4.838 MJ/M3     129.84 BTU/FT3
MOLEC. WT.-DRY GAS               25.746
DENSITY- DRY GAS                  1.070 KG/M3
DRY GAS SENSIBLE HEAT             0.363 MJ/KG
FUEL LATENT HEAT-BOUND WATER     34.13 MJ/HR
                 FREE MOISTURE   10.25 MJ/HR
DRY FUEL ENERGY-HHV             578.49 MJ/HR
                LHV             534.11 MJ/HR
ENERGY IN CHAR                   79.05 MJ/HR        13.66 %
SENSIBLE ENERGY IN GAS           45.10 MJ/HR         7.80 %
CHEMICAL ENERGY IN GAS          311.52 MJ/HR        53.85 %
ENERGY LOSSES                   142.82 MJ/HR        24.69 %
GAS ENERGY              HOT GAS 336.35 MJ/HR
                       COLD GAS 311.52 MJ/HR
EFFICIENCY              HOT GAS  58.14 %
                       COLD GAS  50.35 %
% STOICH AIR                     27.98 %
STOICH AIR           MASS BASIS   5.30 KG/KG FUEL
                   VOLUME BASIS   2.25 M3/MIN
```

```
C.E. GASIFIER RUN 19
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.76 M3/MIN
WET FUEL RATE                    31.30 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                          C      45.590
                          H       5.790
                          O      43.900
FUEL MOISTURE CONTENT            12.90 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.790 MJ/KG
DRY GAS COMPOSITION (% VOL):
                          CO     23.20
                          CO2    10.40
                          CH4     1.43
                          C2H     0.61
                          H2     15.20
                          N2     49.20
                          O2      0.00
GAS TEMPERATURE                 600.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.130 MJ/KG
CHAR MASS FLOWRATE                3.10 KG/HR
CHAR CARBON CONTENT              76.27 % WT
CHAR ENTHALPY (HHV)              26.200 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                54.88 KG/HR
DRY GAS VOLUME FLOWRATE           1.22 M3/MIN
DRY GAS MASS FLOWRATE            78.02 KG/HR
GAS WATER VAPOR MASS FRACTION     9.24 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     7.21 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION     9.18 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE     7.16 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -3.17 KG/HR
EXCESS MASS BY MASS BAL          -2.10 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.424 MJ/M3     145.58 BTU/FT3
LHV AT 298 K                      5.071 MJ/M3     136.11 BTU/FT3
MOLEC. WT.-DRY GAS               25.639
DENSITY- DRY GAS                  1.066 KG/M3
DRY GAS SENSIBLE HEAT             0.368 MJ/KG
FUEL LATENT HEAT-BOUND WATER     30.39 MJ/HR
                 FREE MOISTURE    9.11 MJ/HR
DRY FUEL ENERGY-HHV             512.21 MJ/HR
                LHV             472.70 MJ/HR
ENERGY IN CHAR                   81.22 MJ/HR       15.86 %
SENSIBLE ENERGY IN GAS           41.03 MJ/HR        8.01 %
CHEMICAL ENERGY IN GAS          397.15 MJ/HR       77.54 %
ENERGY LOSSES                    -7.20 MJ/HR       -1.41 %
GAS ENERGY              HOT GAS 412.35 MJ/HR
                       COLD GAS 397.15 MJ/HR
EFFICIENCY              HOT GAS  80.51 %
                       COLD GAS  72.49 %
% STOICH AIR                     37.56 %
STOICH AIR           MASS BASIS   5.36 KG/KG FUEL
                   VOLUME BASIS   2.02 M3/MIN
```

```
C.E. GASIFIER RUN 20
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.82 M3/MIN
WET FUEL RATE                    36.50 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       45.590
                         H        5.790
                         O       43.900
FUEL MOISTURE CONTENT             6.50 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.820 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.10
                         CO2     10.60
                         CH4      1.30
                         C2H      0.56
                         H2      15.20
                         N2      50.20
                         O2       0.00
GAS TEMPERATURE                 712.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.360 MJ/KG
CHAR MASS FLOWRATE                3.20 KG/HR
CHAR CARBON CONTENT              62.98 % WT
CHAR ENTHALPY (HHV)              21.820 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                59.21 KG/HR
DRY GAS VOLUME FLOWRATE           1.29 M3/MIN
DRY GAS MASS FLOWRATE            82.59 KG/HR
GAS WATER VAPOR MASS FRACTION    11.45 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     9.45 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    10.95 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE     9.04 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -0.02 KG/HR
EXCESS MASS BY MASS BAL           0.89 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.217 MJ/M3     140.03 BTU/FT3
LHV AT 298 K                      4.871 MJ/M3     130.73 BTU/FT3
MOLEC. WT.-DRY GAS               25.666
DENSITY- DRY GAS                  1.067 KG/M3
DRY GAS SENSIBLE HEAT             0.511 MJ/KG
FUEL LATENT HEAT-BOUND WATER     38.04 MJ/HR
                 FREE MOISTURE    5.35 MJ/HR
DRY FUEL ENERGY-HHV             642.21 MJ/HR
                LHV             598.82 MJ/HR
ENERGY IN CHAR                   69.82 MJ/HR       10.87 %
SENSIBLE ENERGY IN GAS           60.39 MJ/HR        9.40 %
CHEMICAL ENERGY IN GAS          403.95 MJ/HR       62.90 %
ENERGY LOSSES                   108.05 MJ/HR       16.82 %
GAS ENERGY              HOT GAS 437.53 MJ/HR
                       COLD GAS 403.95 MJ/HR
EFFICIENCY              HOT GAS  68.13 %
                       COLD GAS  58.73 %
% STOICH AIR                     32.38 %
STOICH AIR           MASS BASIS   5.36 KG/KG FUEL
                   VOLUME BASIS   2.53 M3/MIN
```

```
C.E. GASIFIER RUN 21 A
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.71 M3/MIN
WET FUEL RATE                    34.10 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       45.590
                         H        5.790
                         O       43.900
FUEL MOISTURE CONTENT             6.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.930 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      23.50
                         CO2     10.40
                         CH4      1.05
                         C2H      0.45
                         H2      15.30
                         N2      49.30
                         O2       0.00
GAS TEMPERATURE                 707.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.350 MJ/KG
CHAR MASS FLOWRATE                3.60 KG/HR
CHAR CARBON CONTENT              68.71 % WT
CHAR ENTHALPY (HHV)              25.690 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                51.27 KG/HR
DRY GAS VOLUME FLOWRATE           1.14 M3/MIN
DRY GAS MASS FLOWRATE            72.76 KG/HR
GAS WATER VAPOR MASS FRACTION    11.81 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     8.60 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    12.85 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE     9.35 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -0.16 KG/HR
EXCESS MASS BY MASS BAL          -0.34 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.237 MJ/M3     140.55 BTU/FT3
LHV AT 298 K                      4.902 MJ/M3     131.56 BTU/FT3
MOLEC. WT.-DRY GAS               25.648
DENSITY- DRY GAS                  1.066 KG/M3
DRY GAS SENSIBLE HEAT             0.503 MJ/KG
FUEL LATENT HEAT-BOUND WATER     35.50 MJ/HR
                 FREE MOISTURE    5.08 MJ/HR
DRY FUEL ENERGY-HHV             602.85 MJ/HR
                LHV             562.27 MJ/HR
ENERGY IN CHAR                   92.48 MJ/HR       15.34 %
SENSIBLE ENERGY IN GAS           55.77 MJ/HR        9.25 %
CHEMICAL ENERGY IN GAS          357.48 MJ/HR       59.30 %
ENERGY LOSSES                    97.11 MJ/HR       16.11 %
GAS ENERGY             HOT GAS  390.40 MJ/HR
                      COLD GAS  357.48 MJ/HR
EFFICIENCY             HOT GAS   64.76 %
                      COLD GAS   55.51 %
% STOICH AIR                     30.04 %
STOICH AIR          MASS BASIS    5.36 KG/KG FUEL
                  VOLUME BASIS    2.36 M3/MIN
```

```
C.E. GASIFIER RUN 21 B
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              0.82 M3/MIN
WET FUEL RATE                    41.10 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       45.590
                         H        5.790
                         O       43.900
FUEL MOISTURE CONTENT             6.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.930 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      23.00
                         CO2     10.80
                         CH4      1.54
                         C2H      0.66
                         H2      15.50
                         N2      48.50
                         O2       0.00
GAS TEMPERATURE                 827.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.600 MJ/KG
CHAR MASS FLOWRATE                3.60 KG/HR
CHAR CARBON CONTENT              73.46 % WT
CHAR ENTHALPY (HHV)              26.600 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                59.21 KG/HR
DRY GAS VOLUME FLOWRATE           1.34 M3/MIN
DRY GAS MASS FLOWRATE            85.26 KG/HR
GAS WATER VAPOR MASS FRACTION    11.98 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    10.21 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    12.44 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    10.61 KG/HR BY H BAL
EXCESS CARBON BY C BAL            0.20 KG/HR
EXCESS MASS BY MASS BAL           0.85 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.506 MJ/M3     147.79 BTU/FT3
LHV AT 298 K                      5.142 MJ/M3     138.01 BTU/FT3
MOLEC. WT.-DRY GAS               25.600
DENSITY- DRY GAS                  1.064 KG/M3
DRY GAS SENSIBLE HEAT             0.667 MJ/KG
FUEL LATENT HEAT-BOUND WATER     42.79 MJ/HR
                 FREE MOISTURE    6.12 MJ/HR
DRY FUEL ENERGY-HHV             726.60 MJ/HR
                LHV             677.69 MJ/HR
ENERGY IN CHAR                   95.76 MJ/HR       13.18 %
SENSIBLE ENERGY IN GAS           81.15 MJ/HR       11.17 %
CHEMICAL ENERGY IN GAS          441.28 MJ/HR       60.73 %
ENERGY LOSSES                   108.41 MJ/HR       14.92 %
GAS ENERGY             HOT GAS  493.24 MJ/HR
                      COLD GAS  441.28 MJ/HR
EFFICIENCY             HOT GAS   67.88 %
                      COLD GAS   56.72 %
% STOICH AIR                     28.78 %
STOICH AIR          MASS BASIS    5.36 KG/KG FUEL
                  VOLUME BASIS    2.85 M3/MIN
```

```
C.E. GASIFIER RUN 26
INPUT DATA:
TEMPERATURE FOR FLOW RATES       293.16 DEG K
AIR VOLUME FLOW RATE               1.89 M3/MIN
WET FUEL RATE                     79.40 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C        46.020
                         H         5.860
                         O        43.120
FUEL MOISTURE CONTENT             10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)           18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO       22.50
                         CO2      11.50
                         CH4       1.82
                         C2H       0.78
                         H2       16.40
                         N2       47.00
                         O2        0.00
GAS TEMPERATURE                  931.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY         3.830 MJ/KG
CHAR MASS FLOWRATE                10.70 KG/HR
CHAR CARBON CONTENT               50.68 % WT
CHAR ENTHALPY (HHV)               15.880 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                136.48 KG/HR
DRY GAS VOLUME FLOWRATE            3.18 M3/MIN
DRY GAS MASS FLOWRATE            201.54 KG/HR
GAS WATER VAPOR MASS FRACTION      6.31 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     12.71 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION      7.03 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE     14.16 KG/HR BY H BAL
EXCESS CARBON BY C BAL            -8.29 KG/HR
EXCESS MASS BY MASS BAL          -10.52 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                       5.729 MJ/M3      153.75 BTU/FT3
LHV AT 298 K                       5.333 MJ/M3      143.14 BTU/FT3
MOLEC. WT.-DRY GAS                25.442
DENSITY- DRY GAS                   1.058 KG/M3
DRY GAS SENSIBLE HEAT              0.819 MJ/KG
FUEL LATENT HEAT-BOUND WATER      77.72 MJ/HR
                 FREE MOISTURE    19.00 MJ/HR
DRY FUEL ENERGY-HHV             1315.82 MJ/HR
                LHV             1219.10 MJ/HR
ENERGY IN CHAR                   169.92 MJ/HR       12.91 %
SENSIBLE ENERGY IN GAS           197.67 MJ/HR       15.02 %
CHEMICAL ENERGY IN GAS          1091.91 MJ/HR       82.98 %
ENERGY LOSSES                   -143.68 MJ/HR      -10.92 %
GAS ENERGY              HOT GAS 1214.24 MJ/HR
                       COLD GAS 1091.91 MJ/HR
EFFICIENCY              HOT GAS   92.28 %
                       COLD GAS   77.26 %
% STOICH AIR                      35.18 %
STOICH AIR          MASS BASIS     5.47 KG/KG FUEL
                  VOLUME BASIS     5.37 M3/MIN
```

```
C.E. GASIFIER RUN 26 ADJUSTED
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              2.02 M3/MIN
WET FUEL RATE                   105.83 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       46.020
                         H        5.860
                         O       43.120
FUEL MOISTURE CONTENT            10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.50
                         CO2     11.50
                         CH4      1.82
                         C2H      0.78
                         H2      16.40
                         N2      47.00
                         O2       0.00
GAS TEMPERATURE                 931.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.830 MJ/KG
CHAR MASS FLOWRATE               14.13 KG/HR
CHAR CARBON CONTENT              50.68 % WT
CHAR ENTHALPY (HHV)              15.880 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE               145.87 KG/HR
DRY GAS VOLUME FLOWRATE           3.40 M3/MIN
DRY GAS MASS FLOWRATE           215.40 KG/HR
GAS WATER VAPOR MASS FRACTION    11.45 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    24.67 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    12.54 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    27.00 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -1.60 KG/HR
EXCESS MASS BY MASS BAL          -4.84 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.729 MJ/M3     153.75 BTU/FT3
LHV AT 298 K                      5.333 MJ/M3     143.14 BTU/FT3
MOLEC. WT.-DRY GAS               25.442
DENSITY- DRY GAS                  1.058 KG/M3
DRY GAS SENSIBLE HEAT             0.819 MJ/KG
FUEL LATENT HEAT-BOUND WATER    103.59 MJ/HR
                 FREE MOISTURE   25.32 MJ/HR
DRY FUEL ENERGY-HHV            1753.82 MJ/HR
                LHV            1624.91 MJ/HR
ENERGY IN CHAR                  224.38 MJ/HR       12.79 %
SENSIBLE ENERGY IN GAS          244.47 MJ/HR       13.94 %
CHEMICAL ENERGY IN GAS         1167.02 MJ/HR       66.54 %
ENERGY LOSSES                   117.94 MJ/HR        6.73 %
GAS ENERGY              HOT GAS 1330.97 MJ/HR
                       COLD GAS 1167.02 MJ/HR
EFFICIENCY              HOT GAS   75.89 %
                       COLD GAS   61.95 %
% STOICH AIR                      28.21 %
STOICH AIR           MASS BASIS    5.47 KG/KG FUEL
                   VOLUME BASIS    7.16 M3/MIN
```

```
C.E. GASIFIER RUN 27
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              1.86 M3/MIN
WET FUEL RATE                    77.70 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       46.020
                         H        5.860
                         O       43.120
FUEL MOISTURE CONTENT            10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.50
                         CO2     11.50
                         CH4      1.82
                         C2H      0.78
                         H2      16.40
                         N2      47.00
                         O2       0.00
GAS TEMPERATURE                 945.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.860 MJ/KG
CHAR MASS FLOWRATE                8.60 KG/HR
CHAR CARBON CONTENT              51.98 % WT
CHAR ENTHALPY (HHV)              17.730 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE               134.32 KG/HR
DRY GAS VOLUME FLOWRATE           3.13 M3/MIN
DRY GAS MASS FLOWRATE           198.34 KG/HR
GAS WATER VAPOR MASS FRACTION     6.19 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    12.28 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION     6.90 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    13.69 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -7.47 KG/HR
EXCESS MASS BY MASS BAL          -8.61 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.729 MJ/M3     153.75 BTU/FT3
LHV AT 298 K                      5.333 MJ/M3     143.14 BTU/FT3
MOLEC. WT.-DRY GAS               25.442
DENSITY- DRY GAS                  1.058 KG/M3
DRY GAS SENSIBLE HEAT             0.839 MJ/KG
FUEL LATENT HEAT-BOUND WATER     76.05 MJ/HR
                 FREE MOISTURE   18.59 MJ/HR
DRY FUEL ENERGY-HHV            1287.65 MJ/HR
                LHV            1193.00 MJ/HR
ENERGY IN CHAR                  152.48 MJ/HR       11.84 %
SENSIBLE ENERGY IN GAS          198.14 MJ/HR       15.39 %
CHEMICAL ENERGY IN GAS         1074.58 MJ/HR       83.45 %
ENERGY LOSSES                  -137.56 MJ/HR      -10.68 %
GAS ENERGY             HOT GAS 1198.58 MJ/HR
                      COLD GAS 1074.58 MJ/HR
EFFICIENCY             HOT GAS   93.08 %
                      COLD GAS   77.70 %
% STOICH AIR                     35.37 %
STOICH AIR          MASS BASIS    5.47 KG/KG FUEL
                  VOLUME BASIS    5.26 M3/MIN
```

```
C.E. GASIFIER RUN 27 ADJUSTED
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              1.99 M3/MIN
WET FUEL RATE                   101.10 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       46.020
                         H        5.860
                         O       43.120
FUEL MOISTURE CONTENT            10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.50
                         CO2     11.50
                         CH4      1.82
                         C2H      0.78
                         H2      16.40
                         N2      47.00
                         O2       0.00
GAS TEMPERATURE                 945.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.860 MJ/KG
CHAR MASS FLOWRATE               11.19 KG/HR
CHAR CARBON CONTENT              51.98 % WT
CHAR ENTHALPY (HHV)              17.730 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE               143.70 KG/HR
DRY GAS VOLUME FLOWRATE           3.34 M3/MIN
DRY GAS MASS FLOWRATE           212.20 KG/HR
GAS WATER VAPOR MASS FRACTION    10.67 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    22.63 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION    11.69 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    24.82 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -1.63 KG/HR
EXCESS MASS BY MASS BAL          -3.40 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.729 MJ/M3     153.75 BTU/FT3
LHV AT 298 K                      5.333 MJ/M3     143.14 BTU/FT3
MOLEC. WT.-DRY GAS              25.442
DENSITY- DRY GAS                  1.058 KG/M3
DRY GAS SENSIBLE HEAT             0.839 MJ/KG
FUEL LATENT HEAT-BOUND WATER     98.96 MJ/HR
                 FREE MOISTURE   24.19 MJ/HR
DRY FUEL ENERGY-HHV            1675.43 MJ/HR
                LHV            1552.29 MJ/HR
ENERGY IN CHAR                  198.40 MJ/HR       11.84 %
SENSIBLE ENERGY IN GAS          240.75 MJ/HR       14.37 %
CHEMICAL ENERGY IN GAS         1149.69 MJ/HR       68.62 %
ENERGY LOSSES                    86.59 MJ/HR        5.17 %
GAS ENERGY             HOT GAS 1311.11 MJ/HR
                      COLD GAS 1149.69 MJ/HR
EFFICIENCY             HOT GAS   78.26 %
                      COLD GAS   63.89 %
% STOICH AIR                     29.09 %
STOICH AIR          MASS BASIS    5.47 KG/KG FUEL
                  VOLUME BASIS    6.84 M3/MIN
```

```
C.E. GASIFIER RUN 28 A
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              2.09 M3/MIN
WET FUEL RATE                    82.90 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                           C     46.020
                           H      5.860
                           O     43.120
FUEL MOISTURE CONTENT            10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                           CO    23.80
                           CO2   11.20
                           CH4    1.82
                           C2H    0.78
                           H2    16.40
                           N2    46.00
                           O2     0.00
GAS TEMPERATURE                 903.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.770 MJ/KG
CHAR MASS FLOWRATE                8.50 KG/HR
CHAR CARBON CONTENT              48.18 % WT
CHAR ENTHALPY (HHV)              15.620 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE               150.93 KG/HR
DRY GAS VOLUME FLOWRATE           3.59 M3/MIN
DRY GAS MASS FLOWRATE           227.27 KG/HR
GAS WATER VAPOR MASS FRACTION     3.86 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     8.78 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION     5.34 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    12.14 KG/HR BY H BAL
EXCESS CARBON BY C BAL          -11.21 KG/HR
EXCESS MASS BY MASS BAL         -14.08 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.882 MJ/M3     157.85 BTU/FT3
LHV AT 298 K                      5.486 MJ/M3     147.25 BTU/FT3
MOLEC. WT.-DRY GAS               25.393
DENSITY- DRY GAS                  1.056 KG/M3
DRY GAS SENSIBLE HEAT             0.780 MJ/KG
FUEL LATENT HEAT-BOUND WATER     81.14 MJ/HR
                 FREE MOISTURE   19.83 MJ/HR
DRY FUEL ENERGY-HHV            1373.82 MJ/HR
                LHV            1272.84 MJ/HR
ENERGY IN CHAR                  132.77 MJ/HR        9.66 %
SENSIBLE ENERGY IN GAS          202.63 MJ/HR       14.75 %
CHEMICAL ENERGY IN GAS         1266.65 MJ/HR       92.20 %
ENERGY LOSSES                  -228.23 MJ/HR      -16.61 %
GAS ENERGY             HOT GAS 1384.16 MJ/HR
                      COLD GAS 1266.65 MJ/HR
EFFICIENCY             HOT GAS  100.75 %
                      COLD GAS   86.00 %
% STOICH AIR                     37.26 %
STOICH AIR          MASS BASIS    5.47 KG/KG FUEL
                  VOLUME BASIS    5.61 M3/MIN
```

```
C.E. GASIFIER RUN 28 A ADJUSTED
INPUT DATA:
TEMPERATURE FOR FLOW RATES        293.16 DEG K
AIR VOLUME FLOW RATE                2.14 M3/MIN
WET FUEL RATE                     111.96 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C         46.020
                         H          5.860
                         O         43.120
FUEL MOISTURE CONTENT              10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)            18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO        23.80
                         CO2       11.20
                         CH4        1.82
                         C2H        0.78
                         H2        16.40
                         N2        46.00
                         O2         0.00
GAS TEMPERATURE                   903.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY          3.770 MJ/KG
CHAR MASS FLOWRATE                 11.48 KG/HR
CHAR CARBON CONTENT                48.18 % WT
CHAR ENTHALPY (HHV)                15.620 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                 154.54 KG/HR
DRY GAS VOLUME FLOWRATE             3.68 M3/MIN
DRY GAS MASS FLOWRATE             232.70 KG/HR
GAS WATER VAPOR MASS FRACTION      10.01 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE      23.30 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION      11.93 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE      27.76 KG/HR BY H BAL
EXCESS CARBON BY C BAL             -1.68 KG/HR
EXCESS MASS BY MASS BAL            -5.45 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                        5.882 MJ/M3     157.85 BTU/FT3
LHV AT 298 K                        5.486 MJ/M3     147.25 BTU/FT3
MOLEC. WT.-DRY GAS                 25.393
DENSITY- DRY GAS                    1.056 KG/M3
DRY GAS SENSIBLE HEAT               0.780 MJ/KG
FUEL LATENT HEAT-BOUND WATER      109.59 MJ/HR
                 FREE MOISTURE     26.79 MJ/HR
DRY FUEL ENERGY-HHV              1855.40 MJ/HR
                LHV              1719.03 MJ/HR
ENERGY IN CHAR                    179.32 MJ/HR        9.66 %
SENSIBLE ENERGY IN GAS            249.43 MJ/HR       13.44 %
CHEMICAL ENERGY IN GAS           1296.96 MJ/HR       69.90 %
ENERGY LOSSES                     129.69 MJ/HR        6.99 %
GAS ENERGY             HOT GAS   1459.23 MJ/HR
                      COLD GAS   1296.96 MJ/HR
EFFICIENCY             HOT GAS     78.65 %
                      COLD GAS     65.20 %
% STOICH AIR                       28.25 %
STOICH AIR          MASS BASIS      5.47 KG/KG FUEL
                  VOLUME BASIS      7.58 M3/MIN
```

```
C.E. GASIFIER RUN 28 B
INPUT DATA:
TEMPERATURE FOR FLOW RATES      293.16 DEG K
AIR VOLUME FLOW RATE              1.89 M3/MIN
WET FUEL RATE                    77.70 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                         C       46.020
                         H        5.860
                         O       43.120
FUEL MOISTURE CONTENT            10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)          18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                         CO      22.50
                         CO2     11.50
                         CH4      1.82
                         C2H      0.78
                         H2      16.40
                         N2      47.00
                         O2       0.00
GAS TEMPERATURE                 868.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY        3.690 MJ/KG
CHAR MASS FLOWRATE                7.10 KG/HR
CHAR CARBON CONTENT              48.18 % WT
CHAR ENTHALPY (HHV)              15.620 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE               136.48 KG/HR
DRY GAS VOLUME FLOWRATE           3.18 M3/MIN
DRY GAS MASS FLOWRATE           201.54 KG/HR
GAS WATER VAPOR MASS FRACTION     5.86 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE    11.82 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION     6.55 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE    13.20 KG/HR BY H BAL
EXCESS CARBON BY C BAL           -6.99 KG/HR
EXCESS MASS BY MASS BAL          -7.65 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                      5.729 MJ/M3     153.75 BTU/FT3
LHV AT 298 K                      5.333 MJ/M3     143.14 BTU/FT3
MOLEC. WT.-DRY GAS               25.442
DENSITY- DRY GAS                  1.058 KG/M3
DRY GAS SENSIBLE HEAT             0.731 MJ/KG
FUEL LATENT HEAT-BOUND WATER     76.05 MJ/HR
                 FREE MOISTURE   18.59 MJ/HR
DRY FUEL ENERGY-HHV            1287.65 MJ/HR
                LHV            1193.00 MJ/HR
ENERGY IN CHAR                  110.90 MJ/HR        8.61 %
SENSIBLE ENERGY IN GAS          175.50 MJ/HR       13.63 %
CHEMICAL ENERGY IN GAS         1091.91 MJ/HR       84.80 %
ENERGY LOSSES                   -90.67 MJ/HR       -7.04 %
GAS ENERGY             HOT GAS 1192.08 MJ/HR
                      COLD GAS 1091.91 MJ/HR
EFFICIENCY             HOT GAS   92.58 %
                      COLD GAS   78.95 %
% STOICH AIR                     35.94 %
STOICH AIR          MASS BASIS    5.47 KG/KG FUEL
                  VOLUME BASIS    5.26 M3/MIN
```

```
C.E. GASIFIER RUN 28 B ADJUSTED
INPUT DATA:
TEMPERATURE FOR FLOW RATES       293.16 DEG K
AIR VOLUME FLOW RATE               2.12 M3/MIN
WET FUEL RATE                    146.32 KG/HR
DRY FUEL ULTIMATE ANALYSIS (% WT):
                          C        46.020
                          H         5.860
                          O        43.120
FUEL MOISTURE CONTENT              10.60 % DRY BASIS
DRY FUEL ENTHALPY (HHV)            18.540 MJ/KG
DRY GAS COMPOSITION (% VOL):
                          CO       22.50
                          CO2      11.50
                          CH4       1.82
                          C2H       0.78
                          H2       16.40
                          N2       47.00
                          O2        0.00
GAS TEMPERATURE                  868.00 DEGREES K
HOT GAS SAT VAPOR ENTHALPY         3.690 MJ/KG
CHAR MASS FLOWRATE                13.37 KG/HR
CHAR CARBON CONTENT               48.18 % WT
CHAR ENTHALPY (HHV)               15.620 MJ/KG
OUTPUT DATA FOR MASS BALANCE:
AIR MASS FLOWRATE                153.09 KG/HR
DRY GAS VOLUME FLOWRATE            3.56 M3/MIN
DRY GAS MASS FLOWRATE            226.06 KG/HR
GAS WATER VAPOR MASS FRACTION     19.69 % DRY BASIS BY O BAL
GAS WATER VAPOR MASS FLOWRATE     44.52 KG/HR BY O BAL
GAS WATER VAPOR MASS FRACTION     21.37 % DRY BASIS BY H BAL
GAS WATER VAPOR MASS FLOWRATE     48.30 KG/HR BY H BAL
EXCESS CARBON BY C BAL            13.90 KG/HR
EXCESS MASS BY MASS BAL           11.68 KG/HR
OUTPUT DATA FOR ENERGY BALANCE:
HHV AT 298 K                       5.729 MJ/M3       153.75 BTU/FT3
LHV AT 298 K                       5.333 MJ/M3       143.14 BTU/FT3
MOLEC. WT.-DRY GAS                25.442
DENSITY- DRY GAS                   1.058 KG/M3
DRY GAS SENSIBLE HEAT              0.731 MJ/KG
FUEL LATENT HEAT-BOUND WATER     143.22 MJ/HR
                 FREE MOISTURE    35.01 MJ/HR
DRY FUEL ENERGY-HHV             2424.82 MJ/HR
                LHV             2246.59 MJ/HR
ENERGY IN CHAR                   208.84 MJ/HR          8.61 %
SENSIBLE ENERGY IN GAS           285.86 MJ/HR         11.79 %
CHEMICAL ENERGY IN GAS          1224.79 MJ/HR         50.51 %
ENERGY LOSSES                    705.33 MJ/HR         29.09 %
GAS ENERGY            HOT GAS   1426.14 MJ/HR
                     COLD GAS   1224.79 MJ/HR
EFFICIENCY            HOT GAS     58.81 %
                     COLD GAS     47.03 %
% STOICH AIR                      21.41 %
STOICH AIR         MASS BASIS      5.47 KG/KG FUEL
                 VOLUME BASIS      9.90 M3/MIN
```

APPENDIX C

ANALYSIS OF GASIFIER SAMPLES FOR METALS

An analysis of gasifier samples for metals was conducted at the Crocker Nuclear Laboratory, University of California, Davis. The analysis technique used was particle induced x-ray emission (PIXE). The PIXE output is expressed in nanograms per square centimeter of beam area. Because the sample mass in the beam area was not determined, only relative elemental concentrations can be calculated. The gasifier samples analyzed, were collected from Run 28. A description of each sample, the sample preparation, and the corresponding ID number is presented in Table C-1. A copy of the computer printout of the PIXE analysis output is found following Table C-1.

Table C-1

DESCRIPTION OF GASIFIER SAMPLES FOR PIXE ANALYSIS

ID No.	Sample Type[a]	Preparation
1	Fuel	Fuel cubes were broken apart, ground in a blender, ground in a high speed grinder, mixed together, separated into four different sample bags, a sample was drawn from each sample bag.
2	Fuel	
3	Fuel	
4	Fuel	
5	Sludge	Sludge dried at 104°C overnight, ground in a blender.
6	Sludge	Sludge dried at 104°C overnight, ground in a blender and high speed grinder.
7	Char	Char from char pit ground in high speed grinder.
8	Fly ash	Fly ash from high efficiency cyclone, analyzed as collected (no alteration).

---

[a] Samples taken from Run 28

Table C-2

OUTPUT DATA FROM PIXE ANALYSIS OF SLUDGE/WASTEPAPER GASIFIER SAMPLES

```
UC DAVIS PIXE ANALYSIS          TRAY 90941                          ANALYSIS ON 09/10/81      O/P ON 09/11/81
CHEM ENGINEERING (SORRO)

                        AMOUNTS IN  NANOGRAMS/CM**2
                        NO MATRIX CORRECTIONS

ID SLIDE     NA         AL         SI          P          S          CL         K          CA          TI         V
 1  3      301.0*     185.0     4154.1     195.6*     245.3      149.1      675.5     3875.2      903.5     145.5
 2  4      185.9*     323.0     2579.1     120.8*     149.9       80.6      334.9     1822.9      436.5      52.6
 3  5      540.1*     227.4*    4074.7     221.2*     204.0      141.1      767.8     5391.5     1375.9     128.6
 4  6      198.1*     161.0     2691.1     125.7*     108.0       97.9      386.8     2195.8      577.5      54.0
 5  7      557.3*    2535.4    21118.7     232.1*    1115.3      176.2*    3303.6    13421.0     2933.6     266.9
 6  8      525.7*    5260.4    43372.7     444.0     1366.6      259.6*    5928.7    20502.8     4545.3     424.7
 7  9      574.3*    8373.0    38490.5    2038.1      325.5*     283.0*    5481.6    30757.0     7871.2     571.2
 8 10      235.7     6159.3    29591.2    2704.8      350.8      219.6*    4102.0    21277.0     3895.7     111.2*

ID SLIDE     CR         MN         FE         NI         CU         ZN         SE         BR          PB
 1  3      238.5      143.2     5044.0      49.2*     120.4      250.9       87.4*     105.0*     205.1*
 2  4      112.9       75.0     2313.9      29.6*      64.5      132.1       57.2*      68.7*     134.2*
 3  5      386.5      231.1     7660.4      31.8      227.1      402.4       92.1*     110.7*     216.1*
 4  6      146.8       95.0     3165.0      32.1*      79.1      173.5       58.5*      70.3*     137.2*
 5  7      617.8      472.1    32564.3      64.5      675.6     1588.4      120.6*     145.0*     283.0*
 6  8      894.3      577.9    48819.5     171.6     1022.0     2263.5      190.7*     229.2*     601.9
 7  9     1575.8     1346.2    43719.1      94.5     1430.8      567.4      211.1*     253.8*     495.5*
 8 10      515.2      842.0    26149.4      71.4*    2424.4     2185.8      160.3*     192.7*     186.7

          * DENOTES UPPER LIMIT OF ELEMENT NOT FOUND
```

APPENDIX D

A SUMMARY OF THE DRAFT REPORT PREPARED BY ENGINEERING-SCIENCE
EMISSION TESTING OF UNIVERSITY OF CALIFORNIA DAVIS SLUDGE GASIFIER

The United States Environmental Protection Agency (EPA) Environmental Science Research Laboratory (ESRL) and Municipal Environmental Research Laboratory (MERL) have been involved in investigations of the fate of heavy metals and other pollutants during thermal processing of municipal sludge. As part of this investigation, ESRL and MERL issued a Task Order under Division of Stationary Source Enforcement (DSSE) Contract Number 68-01-6312 to Engineering-Science (ES). This Task Order directed emission testing of a pilot scale sludge gasifier and burner developed by research personnel in the University of California, Davis (UCD) Department of Civil Engineering.

The unit tested was a vertical packed bed reactor (VPBR). Sludge was obtained from the UCD wastewater treatment facility and was processed by Papakube in San Diego, California. The dewatered sludge is mixed with shredded paper and densified, producing densified refuse derived fuel (d-RDF). The fuel was gasified in an oxygen-poor atmosphere to produce a combustible gas (termed "producer gas"). A burner was added to the system for the purpose of this test program.

The producer gas stream and the burner flue gas streams were tested during this program. Particulate loading, particle size distribution, gas composition, gas flow rate and particulate characterization sampling were conducted at both test points. In addition, the burner outlet test point was tested for SO_2, total hydrocarbons and NO_x.

SUMMARY OF RESULTS

Particulate Tests

A summary of the tests conducted at the burner (stack) outlet and the producer gas test locations, dates and times of the corresponding runs, is presented in Table D-1.

The results of particulate tests conducted on the U.C. Davis sludge gasifier system are summarized in D-2. The producer gas flow rate is equivalent to the production rate. Producer gas flow ranged from a low of 118 to a high of 130 standard cubic feet per minute. Test Runs 1, 2, and 4 (Run 26, 27, and 28-B) were considered by U.C. Davis representatives to be comparable in production rates. Test Run 3 (Run 28-A) was conducted with the gasifier operating at a higher rate. Based

Table D-1

SCHEDULE OF TESTING CONDUCTED ON U.C. DAVIS SLUDGE GASIFIER

Test	7/13/81	7/14/81	7/15/81	7/16/81
		Stack Outlet Tests		
NO_x	1749-1800 hrs.	1503-1805 hrs.	1054-1655 hrs.	0900-1545 hrs.
THC	1749-1800 hrs.	1503-1805 hrs.	1054-1655 hrs.	0900-1545 hrs.
Method 5		1512-1612 hrs.	1220-1340 hrs.	1007-1107 hrs. & 1318-1418 hrs.
Method 6		1658-1743 hrs.	1220-1305 hrs.	1007-1052 hrs. & 1318-1403 hrs.
Characterization				≈ 1445 hrs.
Particle Sizing				1545-1555 hrs. & 1620-1630 hrs.
		Producer Gas Tests		
Method 5		1514-1559 hrs.	1217-1332 hrs.	1008-1107 hrs. & 1325-1415 hrs.
Particle Sizing		1727-1728.5 hrs.	≈ 1350 hrs.	≈ 1127 hrs.
Characterization				≈ 1440 hrs.

Table D-2

PARTICULATE EMISSIONS SUMMARY - U. C. DAVIS SLUDGE GASIFIER AND BURNER

Location:	Producer Gas	Stack	Producer Gas	Stack	Producer Gas	Stack	Producer Gas	Stack
Run Number:	1	1	2	2	3	3	4	4
Date:	7/14/81	7/14/81	7/15/81	7/15/81	7/16/81	7/16/81	7/16/81	7/16/81
Moisture (%)	12.55	5.64	12.47	5.43	14.73	5.95	15.25	8.35
Orsat Analysis:								
% CO_2	8.5	4.6	10.0	4.8	10.3	5.1	11.8	5.2
% O_2	1.7	19.5	0.5	16.0	0.0	15.3	0.5	15.7
% CO	N/A	0.0	27.5	0.1	N/A	0.0	25.0	0.0
Exhaust Flow Rate (SCFM)	120	514	118	747	130	682	126	603
Stack Temperature (°F)	797	741	824	834	858	833	828	837
Isokinetic (%)	93.8	94.1	107.0	101.9	99.3	111.3	87.6	111.9
Particulate Conc. Front (gr/SCF)	1.126	0.027	0.852	0.021	0.753	0.012	0.693	0.021
Condensible Hydrocarbons (gr/SCF)	0.080	0.007	0.041	0.003	0.100	0.003	0.063	N/A
Emission Rate Front (lb/hr)	1.158	0.122	0.862	0.137	0.839	0.074	0.749	0.106
Condensible Hydrocarbons (lb/hr)	0.083	0.029	0.042	0.017	0.112	0.013	0.067	N/A

upon flow rate measurements, there was little difference in actual producer gas production between the four test runs.

Particulate grain loading in the producer gas ranged from a high of 1.126 grains/SCF during the first test run to a low of 0.693 grains/ SCF during the fourth test run. There was a trend of decreased grain loadings in the producer gas during the series of tests. Grain loadings at the outlet of the burner were, as expected, significantly decreased from loadings in the producer gas stream. Loadings in the burner exhaust gases ranged from 0.012 to 0.027 grains/SCF. The stack gas loadings during the three runs (Run 1, 2, and 4) considered to be normal operation by U.C. Davis representatives were fairly consistent, ranging from 0.021 to 0.027 grains/SCF.

Particulate emission rates from the gasifier ranged from a low of 0.749 to 1.158 pounds per hour. Emission rates from the burner ranged from 0.074 to 0.137 pounds per hour.

Condensed hydrocarbons were determined from an extraction of the back-half catch. Condensible hydrocarbon loadings ranged from 0.041 to 0.100 grains/SCF at the producer gas site and from 0.003 to 0.007 at the stack test site. The corresponding emission rates ranged from 0.042 to 0.112 pounds per hour from the gasifier and 0.013 to 0.029 pounds per hour from the burner.

NO_x and Noncondensible Hydrocarbon Test Results

NO_x and noncondensible hydrocarbon test results from the burner outlet site are summarized in Table D-3. The table includes 15-minute average NO_x and hydrocarbon concentrations and emission rates in addition to daily average concentrations and emission rates. The NO_x and noncondensible hydrocarbon emission rates were determined based on stack gas flow rates measured during the particulate tests. Concentrations were measured for a total of approximately 15 hours of burner operation.

NO_x concentrations ranged from approximately 60 to approximately 115 ppm. The average daily concentrations were 86.2, 79.2, and 80.9 ppm for July 14, 15, 16, respectively. The resulting average emission rates ranged from 0.322 to 0.430 pounds per hour.

Noncondensible hydrocarbon concentrations were measured as hexane. Concentrations exceeded 1 ppm for a brief period on July 15. Calculated emission rates were 0.005, 0.007, and 0.007 pounds per hour for the three test dates.

SO_2 Test Results

As discussed in the section on sampling and analytical procedures, significant deviations from EPA Reference Method 6 occurred during this test program. The results provided in Table D-4 are not considered to be accurate but can be considered reliable approximations of the SO_2 in the burner exhaust gases.

SO_2 concentrations ranged from 0.016 to 0.049 grains per dry standard cubic foot for the four test runs. The resulting emission rates ranged from 0.086 to 0.221

Table D-3

SUMMARY OF NO_x AND NONCONDENSIBLE HYDROCARBON MEASUREMENTS
BURNER OUTLET STACK - U. C. DAVIS SLUDGE GASIFIER

Date	Time	NO_x (ppm)	NO_x lbs./hr.	Noncondensible hydrocarbons As Hexane (ppm)	Noncondensible hydrocarbons lbs./hr.
7/14/81	1515	92.5	0.346	0.60	0.004
	1530	77.5	0.290	0.80	0.006
	1545	75.0	0.280	0.80	0.006
	1600	75.0	0.280	0.85	0.006
	1645	113.5	0.425	0.80	0.006
	1700	87.5	0.327	0.70	0.005
	1715	86.5	0.324	0.50	0.003
	1730	77.5	0.290	0.80	0.006
	1745	89.0	0.333	0.90	0.006
	1800	87.5	0.327	0.60	0.004
	Average	86.2	0.322	0.74	0.005
7/15/81	1054	67.5	0.367	0.80	0.008
	1100	87.5	0.476	0.70	0.007
	1130	75.0	0.408	1.30	0.013
	1200	75.0	0.408	1.00	0.010
	1215	62.5	0.340	0.60	0.006
	1230	90.0	0.489	0.60	0.006
	1245	72.5	0.394	0.60	0.006
	1315	77.5	0.421	0.50	0.005
	1330	91.0	0.495	0.40	0.004
	1345	77.5	0.421	0.40	0.004
	1400	80.0	0.435	0.50	0.005
	1445	95.0	0.516	0.80	0.008
	1515	75.0	0.408	0.80	0.008
	1530	73.8	0.401	0.70	0.007
	1600	105.0	0.571	0.60	0.006
	1615	82.5	0.448	0.60	0.006
	1630	68.5	0.372	0.60	0.006
	1645	70.0	0.380	0.60	0.006
	Average	79.2	0.430	0.70	0.007
7/16/81	0850	77.5	0.384	0.80	0.007
	0900	100.0	0.497	0.80	0.007
	0915	80.0	0.397	0.70	0.006
	0930	77.5	0.384	0.90	0.008
	1000	85.0	0.422	0.99	0.009
	1015	80.0	0.397	0.99	0.009
	1030	68.8	0.342	0.99	0.009
	1045	68.0	0.338	0.99	0.009
	1100	62.5	0.310	0.99	0.009
	1145	88.0	0.437	0.90	0.009
	1215	75.0	0.329	0.70	0.006
	1230	82.0	0.360	0.70	0.006
	1300	80.0	0.351	0.70	0.006
	1315	100.0	0.439	0.75	0.006
	1330	88.0	0.386	0.75	0.006
	1345	85.0	0.373	0.75	0.006
	1400	82.5	0.362	0.60	0.005
	1415	85.0	0.373	0.60	0.005
	1445	85.0	0.373	0.90	0.007
	1500	100.0	0.439	0.90	0.007
	1515	66.0	0.290	0.90	0.007
	1530	65.0	0.285	0.90	0.007
	Average	80.9	0.376	0.83	0.007

Table D-4

SUMMARY OF SO_2 TEST RESULTS
U.C. DAVIS SLUDGE GASIFIER

Test Run	Date	Producer Gas Rate (SCFM)	SO_2 Conc. (grains/DSCF)	SO_2 Emissions (lbs./hr.)
1	7/14/81	120	0.020	0.086
2	7/15/81	118	0.016	0.103
3	7/16/81	130	0.029	0.172
4	7/16/81	126	0.043	0.221

Table D-5

CHARACTERIZATION SAMPLE COLLECTION
July 16, 1981

Producer Gas	Stack Outlet
AA 0.0175114	AA 0.079031
AA 0.080617	AA 0.076160
AA 0.088875	AA 0.080372
AA 0.080678	AA 0.077568
AA 0.081490	TE 370.127440
AA 0.076437	TE 370.125174
TE 0.132094	TE 370.126493
TE 0.124647	GF 0.130184
TE 0.130456	GF 0.136580
GF 0.138595	GF 0.132140
GF 0.137318	GF 0.139711
GF 0.135967	GF-A 0.122688
GF 0.134570	FS 0.111343
GF-A 0.120030	FS 0.108487
GF 0.135581	FS 0.110634
FS 0.108973	
FS 0.110465	
FS 0.115327	

pounds per hour. Gas flow rates used to determine emission rates were determined during particulate test runs.

Characterization Samples

The samples collected to characterize the gasifier process streams are presented in Table D-5. Filter numbers are listed under the appropriate test location. The results of the analyses of these filters were not made available by EPA for presentation in this report. Analyses of characterization samples were performed by EPA in Research Triangle Park, North Carolina.

Particle Size Determinations

Four particle size determinations were conducted: three sample runs at a location which provided sampling of the producer gas, and one sample run at the stack outlet of the sludge gasifier. Data for each run are presented as graphs in Figures D-1 and D-2. The aerodynamic diameter (in microns) is plotted on the ordinant, and the percent mass loading less than the stated size is plotted on the abscissa. For additional reference, the greater than stated size is presented on the upper abscissa.

The graphs were prepared using data from computer printouts presented in Appendix F in Reference 15. The method of calculating the aerodynamic diameter utilized the Task Group on Lung Dynamics (TGLD) definition, i.e. an assumption of spherical particle shape is made, and the density of the particulate material is assigned a value of 1.00 g/cm^3, D_{50}, cutpoint determination retains the calculation of the Cunningham slip factor. The calculations employ determination of gas viscocity using the moisture determination obtained during the Method 5 tests. Following standard conventions, the particulate matter catch recovered from the precipitate is included with the catch of the zero stage.

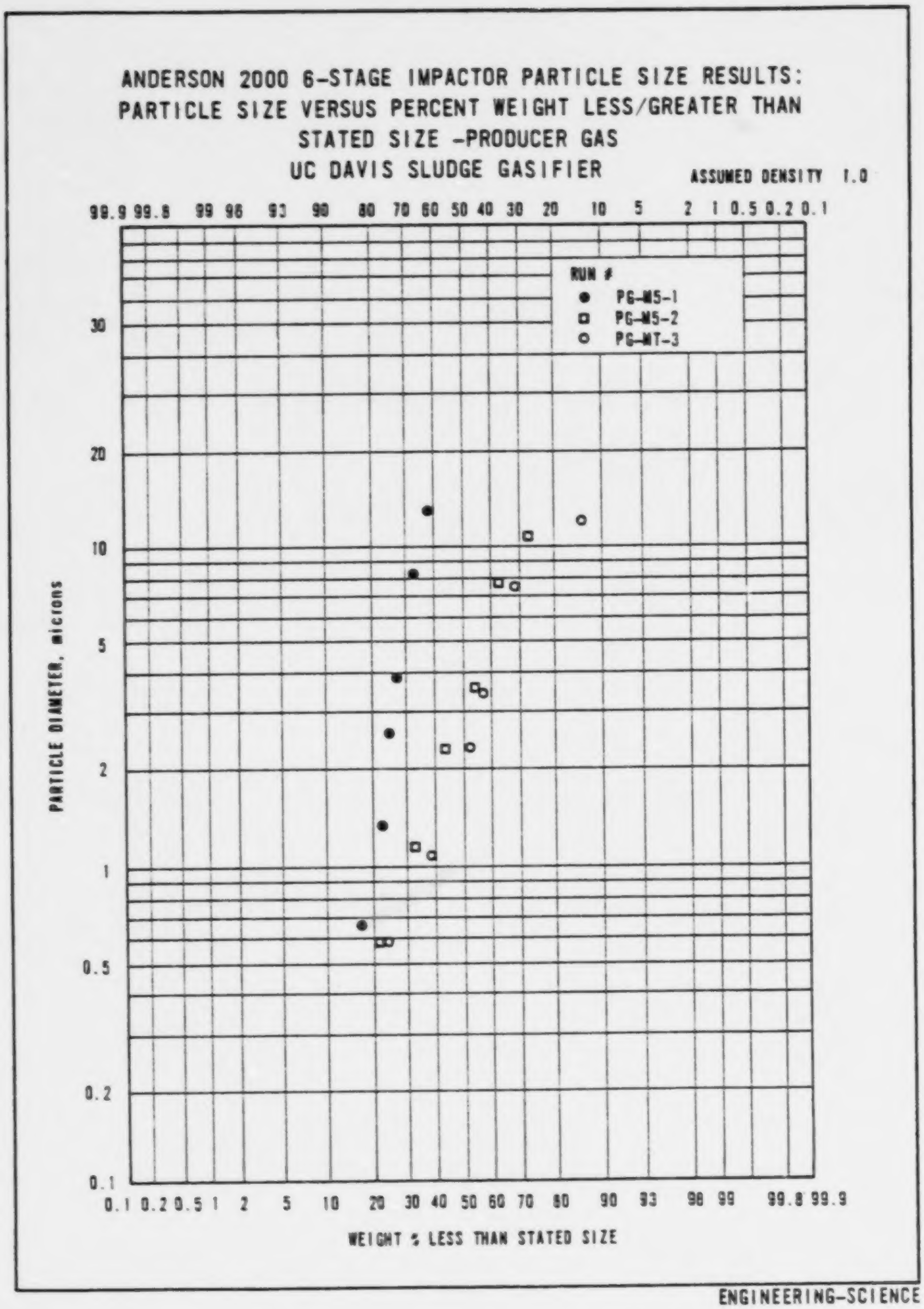
The data for the producer gas show a range in particle size of 0.5 micron to 13.5 microns, with the majority of the particles larger than 12.0 microns (percent cumulation greater than 50 percent) for PG-M5-1 (Run 26). Particle size data collected from Runs 27 and 28-A (PG-M5-2 and PG-MT-3) are considerably different from the data collected during Run 26. The D_{50} for the particles in the producer gas for Runs 27 and 28-A is about 3 microns.

The particles were black and "carbon-like" in appearance. The grain loading at the producer gas location was extremely heavy and required very short duration sample runs.

The outlet stack data (PS-50-1), collected during Run 28-B showed particles considerably smaller than those collected from the producer gas during Run 26. The majority of the particles are in 8.3 micron range.

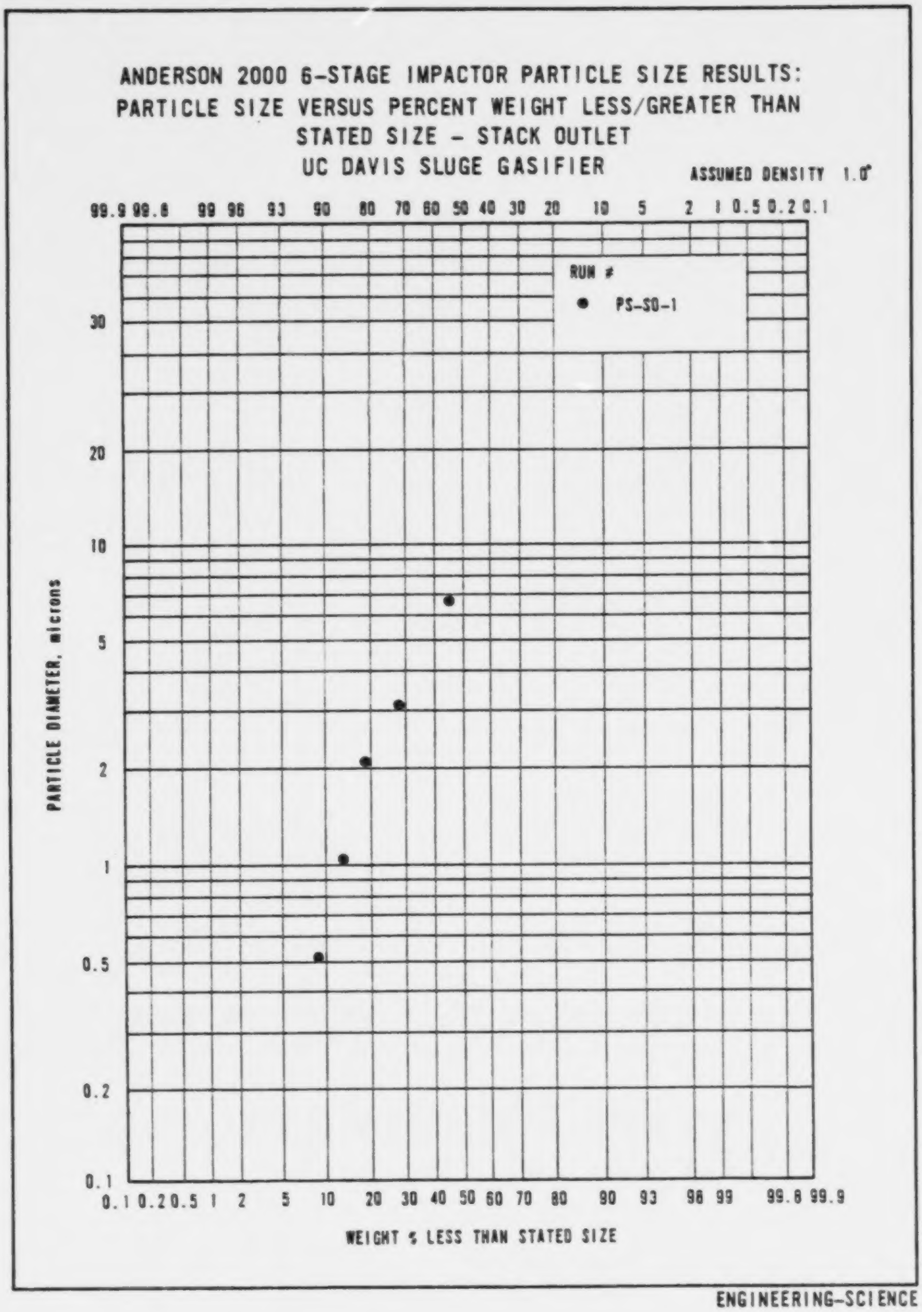
SAMPLING LOCATION

Sampling was conducted simultaneously at two locations in the UCD sludge gasification system. The producer gas stream was sampled down-stream of the cyclone separator and upstream of the combustion air injection (Figure D-3). A single 4-inch test port was used for sampling the producer gas stream. The port



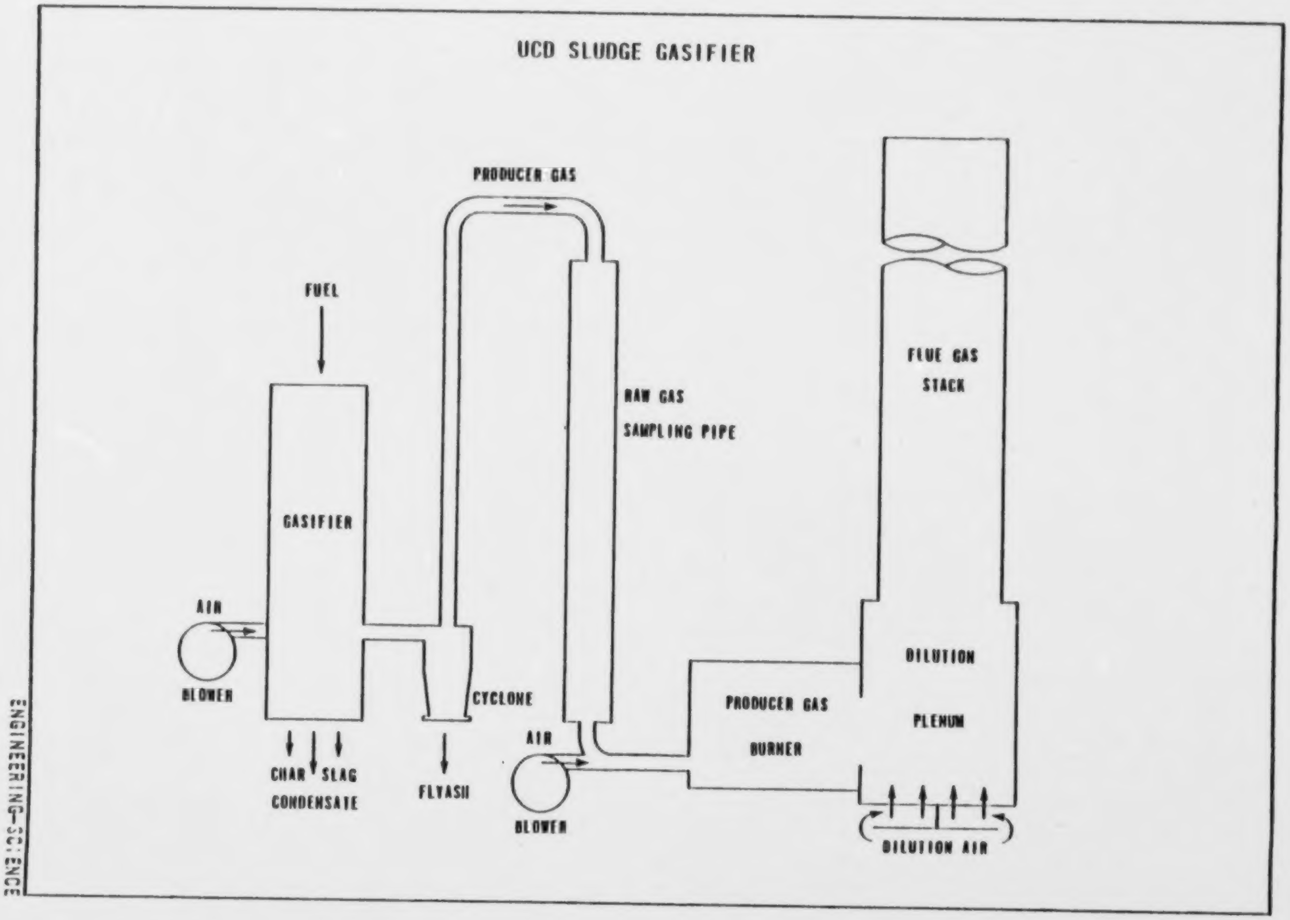
ENGINEERING-SCIENCE

Figure D-1



ENGINEERING-SCIENCE

Figure D-2


UCD SLUDGE GASIFIER

PRODUCER GAS
FUEL
GASIFIER
AIR
BLOWER
CHAR
SLAG
CONDENSATE
CYCLONE
FLYASH
RAW GAS
SAMPLING PIPE
AIR
BLOWER
PRODUCER GAS
BURNER
FLUE GAS
STACK
DILUTION
PLENUM
DILUTION AIR

ENGINEERING-SCIENCE

Figure D-3

was located in a 9.5-inch internal diameter duct. The nearest upstream disturbance (a 90° elbow) was 78 inches (8.2 duct diameters) from the test port and the nearest downstream disturbance (a 90° elbow) was 19 inches (2 duct diameters) from the test port. Since only one test port was available, eight points were sampled on a single traverse.

Exhaust gases from the producer gas burner were sampled from ports located in the 18-inch diameter stack. Test ports were located 144 inches (8 duct diameters) above the dilution plenum and 36 inches (2 duct diameters) below the stack exit. Four points were used per traverse for determination of stack gas velocity.

SAMPLING AND ANALYTICAL PROCEDURES

Particulate Sampling Procedures

EPA Reference Method 5 was employed for particulate sample collection during this program. A preliminary velocity traverse was conducted prior to each test run and a sampling point of average velocity selected for sampling. Particulate sampling was conducted for 60 minutes for each of the four stack samples. The producer gas sampling time varied from 45 to 55 minutes due to overloading of filters and the necessity of interrupting the test to make the required filter change. No leak check could be accomplished prior to or after these filter changes due to the explosion hazard involved in opening the producer gas test port. Filters were changed with the probe in place in the gas stream.

The velocity was monitored at the sample point to allow isokinetic sampling. Three tests were conducted out of the specified isokinetic sampling rate of 100 ± 10%.

The borosilicate glass-lined probes were rinsed with acetone following each test. The back-half catch was recovered and saved for analysis of condensible hydrocarbons. A back-half rinse with acetone followed the water rinse. The acetone fraction was recovered separately. A chloroform ether extraction was performed on a portion of the back-half water catch for determination of condensible hydrocarbons.

Noncondensible Hydrocarbons and NO_x

A sample of the stack gas was extracted through a stainless steel probe. The gas was then passed through a condenser to remove moisture and condensible hydrocarbons. The dried gas was drawn through an unheated Teflon sample line, a vacuum gage, a needle valve, and a pump equipped with a stainless steel head. The entire sample was introduced into a TECO 44 NO_x Analyzer. The analyzer bypass was then diverted to a Scott Model 215 Total Hydrocarbon Analyzer.

All instrument calibrations were accomplished by introducing span gas directly into the analyzers. Following instrument spans, span gas was introduced into the sampling system at the probe to determine if there was system leakage or line loss. In addition, the sampling system was leak checked at 24 inches of mercury vacuum.

Instrument calibrations were performed prior to each test. A span check through the sample line was conducted after each test. Instrument drift was one percent or less for all test runs.

Hydrocarbon calibrations were accomplished using hexane in zero air calibration vixtures. The NO_x analyzer was calibrated using NO in nitrogen. All calibration gas mixtures were certified by the manufacturer to be within ± 2 percent of the cylinder tag value.

Particle Size Determinations

Particle size distributions were determined using Andersen 2000 Six-Stage Impactors. The impactors were positioned in the stack which allowed in-situ size separation. Stack gas velocities were determined during preliminary velocity tests. A point of average velocity was selected and that point was used for particle size sampling.

Due to the explosion hazard related to opening the producer gas port during gasifier operation, each Andersen sample was left in the duct for approximately one hour. Each particle size run was approximately one-half minute in duration due to the high inlet grain loadings encountered in the producer gas.

Glass fiber filter substrates were used for sample collection. They were conditioned and weighed in the ES Arcadia Laboratory on a Cahn Model 26 Electromagnetic Balance.

SO_2 Sample Collection

ES employed EPA Reference Method 6 sample train for determination of SO_2 in the stack gas stream. All samples were collected for a 45 minute period. Sample collection rates were 1 cubic foot per hour for the first two test runs, and 1.5 cubic feet per hour for the second two test runs. The meter box operator failed to record meter volumes and temperatures. Gas volumes were estimated based on the sampling rate as noted on the rotometer and a gas meter temperature for all test runs of 90°F. This method of gas volume estimation will allow approximation of SO_2 emission rates only.

Samples were recovered and analyzed according to EPA Method 6 procedures. Laboratory analyses were performed in the ES laboratory in Arcadia, California.

```
                    PARTICULATE EMISSION DATA REPORT

   PG-M5-1  UC DAVIS SLUDGE GASIFIER PRODUCER GAS JULY 14,1981

           BAROMETRIC PRESSURE (IN. HG)                            29.94
           AVG. ORIFICE PRES. DROP (IN. H2O)                        0.310
           VOLUME OF DRY GAS SAMPLED, METER COND.(DCF)             15.462
           DRY GAS METER GAMMA                                      0.990
           AVG. METER TEMP. (F)                                   115.1
           VOLUME OF DRY GAS SAMPLED (DSCF)                        14.074

           TOTAL H2O COLLECTED (ML)                                42.9
           VOLUME OF H2O COLLECTED (SCF)                            2.02
           % MOISTURE IN STACK GAS BY VOLUME                       12.58
           MOLE FRACTION OF DRY GAS                                 0.874

           % CARBON DIOXIDE                                         8.53
           % OXYGEN                                                 1.73
           % CARBON MONOXIDE                                        9.60
           MOLECULAR WEIGHT OF DRY GAS                             29.43
           MOLECULAR WEIGHT OF STACK GAS                           28.00

           AVERAGE STACK GAS VELOCITY, STACK COND. (FPS)           10.3
           AVERAGE STACK GAS TEMPERATURE (F)                      797.2
           ABSOLUTE STACK GAS PRESSURE (IN. HG)                    30.03
           STACK GAS FLOW RATE (ACFM)                             304.
           STACK GAS FLOW RATE (DSCFM)                            112.

           NET TIME OF TEST (MIN.)                                 45.
           STACK DIAMETER (IN.)                                     9.5
           SAMPLING NOZZLE DIAMETER (IN.)                           0.501
           % ISOKINETIC                                           100.3

           PARTICULATE MASS  PROBE+CYC+FIL (MG)                  1027.2
           PARTICULATE MASS TOTAL (MG)                             72.9

           PART. CONC.-FRONT HALF (GR/DSCF)                         1.124
           PART. CONC.-TOTAL (GR/DSCF)                              0.080
           PART. CONC.-FRONT HALF @ STACK COND. (GR/CF)             0.414
           PART. CONC.-TOTAL @ STACK COND. (GR/CF)                  0.029

           EMISSION RATE-FRONT HALF- (LB/HR)                        1.080
           EMISSION RATE-TOTAL- (LB/HR)                             0.077

           % EXCESS AIR                                           -12.7

              STANDARD CONDITIONS  *68 DEG F  *29.92 IN. HG

                          ENGINEERING SCIENCE INC.
                              ARCADIA, CALIF.
                    PARTICULATE EMISSION DATA REPORT
 ---------------------------------------------------------------------------
       PG-M5-2  UC DAVIS SLUDGE GLASIFIER PRODUCER GAS JULY 15,1981

 ---------------------------------------------------------------------------
            BAROMETRIC PRESSURE (IN. HG)                          29.93
            AVG. ORIFICE PRES. DROP (IN. H2O)                      0.401
            VOLUME OF DRY GAS SAMPLED, METER COND.(DCF)           12.129
 ---------------------------------------------------------------------------
            DRY GAS METER GAMMA                                    0.990
            AVG. METER TEMP. (F)                                 107.5
            VOLUME OF DRY GAS SAMPLED (DSCF)                      17.534
 ---------------------------------------------------------------------------

            TOTAL H2O COLLECTED (ML)                              53.2
            VOLUME OF H2O COLLECTED (SCF)                          2.51
 ---------------------------------------------------------------------------
            % MOISTURE IN STACK GAS BY VOLUME                     12.50
            MOLE FRACTION OF DRY GAS                               0.875

 ---------------------------------------------------------------------------
            % CARBON DIOXIDE                                      10.00
            % OXYGEN                                               0.47
            % CARBON MONOXIDE                                     27.50
 ---------------------------------------------------------------------------
            MOLECULAR WEIGHT OF DRY GAS                           29.62
            MOLECULAR WEIGHT OF STACK GAS                         28.17

 ---------------------------------------------------------------------------
            AVERAGE STACK GAS VELOCITY, STACK COND. (FPS)    [illegible]
            AVERAGE STACK GAS TEMPERATURE (F)                    823.5
            ABSOLUTE STACK GAS PRESSURE (IN. HG)                  29.92
 ---------------------------------------------------------------------------
            STACK GAS FLOW RATE (ACFM)                           305.
            STACK GAS FLOW RATE (DSCFM)                          110.

 ---------------------------------------------------------------------------
            NET TIME OF TEST (MIN.)                               50.
            STACK DIAMETER (IN.)                                   3.5
            SAMPLING NOZZLE DIAMETER (IN.)                         0.501
 ---------------------------------------------------------------------------
            % ISOKINETIC                                         114.8

            PARTICULATE MASS  PROBE+CYC+FIL (MG)                 970.3
 ---------------------------------------------------------------------------
            PARTICULATE MASS TOTAL (MG)                           47.4

            PART. CONC.-FRONT HALF (GR/DSCF)                       0.150
 ---------------------------------------------------------------------------
            PART. CONC.-TOTAL (GR/DSCF)                            0.042
            PART. CONC.-FRONT HALF @ STACK COND. (GR/CF)           0.306
            PART. CONC.-TOTAL @ STACK COND. (GR/CF)                0.015
 ---------------------------------------------------------------------------

            EMISSION RATE-FRONT HALF- (LB/HR)                      0.803
            EMISSION RATE-TOTAL- (LB/HR)                           0.039
 ---------------------------------------------------------------------------

            F FACTOR (DSCF/10**6BTU)                               0.
            EMISSION RATE-FRONT HALF- (LB/10**6BTU)                0.000
 ---------------------------------------------------------------------------
            EMISSION RATE-TOTAL- (LB/10**6BTU)                     0.000

            % EXCESS AIR                                         -41.5
 ---------------------------------------------------------------------------


              STANDARD CONDITIONS  *68 DEG F  *29.92 IN. HG
 ---------------------------------------------------------------------------


                        ENGINEERING SCIENCE INC.
 ---------------------------------------------------------------------------
                            ARCADIA, CALIF.
```

```
                 PARTICULATE EMISSION DATA REPORT

   PG-M5-3  UC DAVIS SLUDGE GASIFIER PRODUCER GAS JULY 16,1981

          BAROMETRIC PRESSURE (IN. HG)                          29.76
          AVG. ORIFICE PRES. DROP (IN. H2O)                      0.435
          VOLUME OF DRY GAS SAMPLED, METER COND.(DCF)           20.560
          DRY GAS METER GAMMA                                    0.990
          AVG. METER TEMP. (F)                                  81.4
          VOLUME OF DRY GAS SAMPLED (DSCF)                      19.764

          TOTAL H2O COLLECTED (ML)                              72.5
          VOLUME OF H2O COLLECTED (SCF)                          3.42
          % MOISTURE IN STACK GAS BY VOLUME                     14.76
          MOLE FRACTION OF DRY GAS                               0.852

          % CARBON DIOXIDE                                      10.33
          % OXYGEN                                               0.06
          % CARBON MONOXIDE                                      0.00
          MOLECULAR WEIGHT OF DRY GAS                           29.65
          MOLECULAR WEIGHT OF STACK GAS                         27.93

          AVERAGE STACK GAS VELOCITY, STACK COND. (FPS)         12.1
          AVERAGE STACK GAS TEMPERATURE (F)                    858.2
          ABSOLUTE STACK GAS PRESSURE (IN. HG)                  29.85
          STACK GAS FLOW RATE (ACFM)                           357.
          STACK GAS FLOW RATE (DSCFM)                          121.

          NET TIME OF TEST (MIN.)                               55.
          STACK DIAMETER (IN.)                                   9.5
          SAMPLING NOZZLE DIAMETER (IN.)                         0.501
          % ISOKINETIC                                         106.4

          PARTICULATE MASS  PROBE+CYC+FIL (MG)                 964.1
          PARTICULATE MASS TOTAL (MG)                          128.8

          PART. CONC.-FRONT HALF (GR/DSCF)                       0.751
          PART. CONC.-TOTAL (GR/DSCF)                            0.100
          PART. CONC.-FRONT HALF @ STACK COND. (GR/CF)           0.256
          PART. CONC.-TOTAL @ STACK COND. (GR/CF)                0.034

          EMISSION RATE-FRONT HALF- (LB/HR)                      0.782
          EMISSION RATE-TOTAL- (LB/HR)                           0.104

          F FACTOR (DSCF/10**6BTU)                               0.
          EMISSION RATE-FRONT HALF- (LB/10**6BTU)               0.000
          EMISSION RATE-TOTAL- (LB/10**6BTU)                     0.000

          % EXCESS AIR                                           0.0


              STANDARD CONDITIONS  *68 DEG F  *29.92 IN. HG


                        ENGINEERING SCIENCE INC.
                          ARCADIA, CALIF.
```

```
                    PARTICULATE EMISSION DATA REPORT

PG-M5-4  UC DAVIS SLUDGE GASIFIER PRODUCER GAS JULY 16,1981

          BAROMETRIC PRESSURE (IN. HG)                          29.77
          AVG. ORIFICE PRES. DROP (IN. H2O)                      0.332
          VOLUME OF DRY GAS SAMPLED, METER COND.(DCF)           16.691
          DRY GAS METER GAMMA                                    0.990
          AVG. METER TEMP. (F)                                 104.1
          VOLUME OF DRY GAS SAMPLED (DSCF)                      15.350

          TOTAL H2O COLLECTED (ML)                              58.7
          VOLUME OF H2O COLLECTED (SCF)                          2.77
          % MOISTURE IN STACK GAS BY VOLUME                     15.29
          MOLE FRACTION OF DRY GAS                               0.847

          % CARBON DIOXIDE                                      11.80
          % OXYGEN                                               0.50
          % CARBON MONOXIDE                                     25.06
          MOLECULAR WEIGHT OF DRY GAS                           29.91
          MOLECULAR WEIGHT OF STACK GAS                         28.09

          AVERAGE STACK GAS VELOCITY, STACK COND. (FPS)         11.5
          AVERAGE STACK GAS TEMPERATURE (F)                    828.0
          ABSOLUTE STACK GAS PRESSURE (IN. HG)                  29.76
          STACK GAS FLOW RATE (ACFH)                           339.
          STACK GAS FLOW RATE (DSCFH)                          117.

          NET TIME OF TEST (MIN.)                               56.
          STACK DIAMETER (IN.)                                   9.5
          SAMPLING NOZZLE DIAMETER (IN.)                         0.501
          % ISOKINETIC                                          96.3

          PARTICULATE MASS  PROBE+CYC+FIL (MG)                 689.9
          PARTICULATE MASS TOTAL (MG)                           62.1

          PART. CONC.-FRONT HALF (GR/DSCF)                       0.692
          PART. CONC.-TOTAL (GR/DSCF)                            0.062
          PART. CONC.-FRONT HALF @ STACK COND. (GR/CF)           0.239
          PART. CONC.-TOTAL @ STACK COND. (GR/CF)                0.022

          EMISSION RATE-FRONT HALF- (LB/HR)                      0.695
          EMISSION RATE-TOTAL- (LB/HR)                           0.063

          F FACTOR (DSCF/10**6BTU)                               0.
          EMISSION RATE-FRONT HALF- (LB/10**6BTU)                0.000
          EMISSION RATE-TOTAL- (LB/10**6BTU)                     0.000

          % EXCESS AIR                                         -42.0

               STANDARD CONDITIONS  *68 DEG F  *29.92 IN. HG

                        ENGINEERING SCIENCE I.C.
                             ARCADIA, CALIF.
```

```
                 PARTICULATE EMISSION DATA REPORT
                          METRIC SYSTEM

SO-45-1  UC DAVIS SLUDGE GLASIFIER STACK OUTLET JULY 14,1981

          BAROMETRIC PRESSURE (MM HG)                          761.
          AVG. ORIFICE PRES. DROP (MM H2O)                      14.16
          VOLUME OF DRY GAS SAMPLED, METER COND.(M3)             0.641
          DRY GAS METER GAMMA                                   0.998
          AVG. METER TEMP. (C)                                  53.8
          VOLUME OF DRY GAS SAMPLED (NM3)                        0.606

          TOTAL H2O COLLECTED (ML)                              27.1
          VOLUME OF H2O COLLECTED (NM3)                          0.036
          % MOISTURE IN STACK GAS BY VOLUME                      5.59
          MOLE FRACTION OF DRY GAS                               0.944

          % CARBON DIOXIDE                                      4.60
          % OXYGEN                                             19.53
          % CARBON MONOXIDE                                     0.00
          MOLECULAR WEIGHT OF DRY GAS                          29.52
          MOLECULAR WEIGHT OF STACK GAS                        28.87

          AVERAGE STACK GAS VELOCITY, STACK COND. (MPS)          3.56
          AVERAGE STACK GAS TEMPERATURE (C)                    303.4
          ABSOLUTE STACK GAS PRESSURE (MM HG)                  761.
          STACK GAS FLOW RATE (M3/M)                           35.03
          STACK GAS FLOW RATE (NM3/M)                          11.55

          NET TIME OF TEST (MIN.)                              60.
          STACK DIAMETER (M)                                     0.457
          SAMPLING NOZZLE DIAMETER (CM)                          1.242
          % ISOKINETIC                                         94.1

          PARTICULATE MASS  PROBE+CYC+FIL (MG)                 38.3
          PARTICULATE MASS TOTAL (MG)                           9.4

          PART. CONC.-FRONT HALF (MG/NM3)                      63.035
          PART. CONC.-TOTAL (MG/NM3)                           15.471
          PART. CONC.-FRONT HALF @ STACK COND. (MG/M3)         26.191
          PART. CONC.-TOTAL @ STACK COND. (MG/M3)               6.428

          EMISSION RATE-FRONT HALF- (KG/HR)                     0.055
          EMISSION RATE-TOTAL- (KG/HR)                          0.014

          F FACTOR ( NM3/10**6BTU)                              0.00
          EMISSION RATE-FRONT HALF- (KG/10**6BTU)               0.000
          EMISSION RATE-TOTAL- (KG/10**6BTU)                    0.000

          % EXCESS AIR                                       3902.5

             STANDARD CONDITIONS  *20 DEG C  *760 MM HG

                      ENGINEERING SCIENCE INC.
                          ARCADIA, CALIF.
```

```
                PARTICULATE EMISSION DATA REPORT
                        METRIC SYSTEM
-----------------------------------------------------------------------
   SO-M5-2  UC DAIVS SLUDGE GASIFIER STACK OUTLET JULY 15,1981

-----------------------------------------------------------------------
        BAROMETRIC PRESSURE (MM HG)                          758.
        AVG. ORIFICE PRES. DROP (MM H2O)                      33.43
        VOLUME OF DRY GAS SAMPLED, METER COND.(M3)             1.051
-----------------------------------------------------------------------
        DRY GAS METER GAMMA                                    0.990
        AVG. METER TEMP. (C)                                  47.1
        VOLUME OF DRY GAS SAMPLED (NM3)                        0.954
-----------------------------------------------------------------------

        TOTAL H2O COLLECTED (ML)                              41.0
        VOLUME OF H2O COLLECTED (NM3)                          0.055
-----------------------------------------------------------------------
        % MOISTURE IN STACK GAS BY VOLUME                      5.43
        MOLE FRACTION OF DRY GAS                               0.946
-----------------------------------------------------------------------

        % CARBON DIOXIDE                                       4.80
        % OXYGEN                                              15.97
        % CARBON MONOXIDE                                      0.10
-----------------------------------------------------------------------
        MOLECULAR WEIGHT OF DRY GAS                           29.41
        MOLECULAR WEIGHT OF STACK GAS                         28.79
-----------------------------------------------------------------------

        AVERAGE STACK GAS VELOCITY, STACK COND. (MPS)          5.57
        AVERAGE STACK GAS TEMPERATURE (C)                    445.3
        ABSOLUTE STACK GAS PRESSURE (MM HG)                  758.
-----------------------------------------------------------------------
        STACK GAS FLOW RATE (M3/M)                            54.91
        STACK GAS FLOW RATE (NM3/M)                           21.14
-----------------------------------------------------------------------

        NET TIME OF TEST (MIN.)                               60.
        STACK DIAMETER (M)                                     0.457
        SAMPLING NOZZLE DIAMETER (CM)                          1.242
-----------------------------------------------------------------------
        % ISOKINETIC                                         101.9

-----------------------------------------------------------------------
        PARTICULATE MASS  PROBE+CYC+FIL (MG)                  46.8
        PARTICULATE MASS TOTAL (MG)                            5.8

-----------------------------------------------------------------------
        PART. CONC.-FRONT HALF (MG/NM3)                       48.975
        PART. CONC.-TOTAL (MG/NM3)                             6.070
        PART. CONC.-FRONT HALF @ STACK COND. (MG/M3)          18.854
        PART. CONC.-TOTAL @ STACK COND. (MG/M3)                2.337
-----------------------------------------------------------------------

        EMISSION RATE-FRONT HALF- (KG/HR)                      0.062
        EMISSION RATE-TOTAL- (KG/HR)                           0.008
-----------------------------------------------------------------------

        F FACTOR ( NM3/10**6BTU)                               0.00
        EMISSION RATE-FRONT HALF- (KG/10**6BTU)                0.000
        EMISSION RATE-TOTAL- (KG/10**6BTU)                     0.000

-----------------------------------------------------------------------
        % EXCESS AIR                                         320.3

-----------------------------------------------------------------------
           STANDARD CONDITIONS  *20 DEG C  *760 MM HG

-----------------------------------------------------------------------
                  ENGINEERING SCIENCE INC.
                      ARCADIA, CALIF.
```

```
                 PARTICULATE EMISSION DATA REPORT
                          METRIC SYSTEM
-----------------------------------------------------------------
    SO-M5-3  UC DAVIS SLUDGE GASIFIER STACK OUTLET JULY 16,1981
-----------------------------------------------------------------
        BAROMETRIC PRESSURE (MM HG)                        756.
        AVG. ORIFICE PRES. DROP (MM H2O)                    29.74
        VOLUME OF DRY GAS SAMPLED, METER COND.(M3)          1.019
        DRY GAS METER GAMMA                                 0.990
        AVG. METER TEMP. (C)                               37.0
        VOLUME OF DRY GAS SAMPLED (NM3)                     0.951

        TOTAL H2O COLLECTED (ML)                           45.0
        VOLUME OF H2O COLLECTED (NM3)                       0.060
        % MOISTURE IN STACK GAS BY VOLUME                   5.95
        MOLE FRACTION OF DRY GAS                            0.941

        % CARBON DIOXIDE                                    5.06
        % OXYGEN                                           15.33
        % CARBON MONOXIDE                                   0.00
        MOLECULAR WEIGHT OF DRY GAS                        29.42
        MOLECULAR WEIGHT OF STACK GAS                      28.74

        AVERAGE STACK GAS VELOCITY, STACK COND. (MPS)       5.14
        AVERAGE STACK GAS TEMPERATURE (C)                 445.2
        ABSOLUTE STACK GAS PRESSURE (MM HG)               756.
        STACK GAS FLOW RATE (M3/M)                         50.60
        STACK GAS FLOW RATE (NM3/M)                        19.32

        NET TIME OF TEST (MIN.)                            60.
        STACK DIAMETER (M)                                  0.457
        SAMPLING NOZZLE DIAMETER (CM)                       1.242
        % ISOKINETIC                                      111.3

        PARTICULATE MASS  PROBE+CYC+FIL (MG)               27.4
        PARTICULATE MASS TOTAL (MG)                         5.0

        PART. CONC.-FRONT HALF (MG/NM3)                    28.743
        PART. CONC.-TOTAL (MG/NM3)                          5.245
        PART. CONC.-FRONT HALF @ STACK COND. (MG/M3)       10.976
        PART. CONC.-TOTAL @ STACK COND. (MG/M3)             2.003

        EMISSION RATE-FRONT HALF- (KG/HR)                   0.033
        EMISSION RATE-TOTAL- (KG/HR)                        0.006

        F FACTOR ( NM3/10**6BTU)                            0.00
        EMISSION RATE-FRONT HALF- (KG/10**6BTU)             0.000
        EMISSION RATE-TOTAL- (KG/10**6BTU)                  0.000

        % EXCESS AIR                                      269.4
-----------------------------------------------------------------
              STANDARD CONDITIONS  *20 DEG C  *760 MM HG
-----------------------------------------------------------------
                     ENGINEERING SCIENCE INC.
                          ARCADIA, CALIF.
```

```
                PARTICULATE EMISSION DATA REPORT
                         METRIC SYSTEM
-------------------------------------------------------------------
 SO-HS-4  UC DAVIS SLUDGE GASIFIER STACK OUTLET JULY 16,1981

-------------------------------------------------------------------
       BAROMETRIC PRESSURE (MM HG)                          756.
       AVG. ORIFICE PRES. DROP (MM H2O)                      24.13
       VOLUME OF DRY GAS SAMPLED, METER COND.(M3)             0.920
       DRY GAS METER GAMMA                                    0.990
       AVG. METER TEMP. (C)  -                               41.5
       VOLUME OF DRY GAS SAMPLED (NM3)                        0.846

       TOTAL H2O COLLECTED (ML)                              57.7
       VOLUME OF H2O COLLECTED (NM3)                          0.077
       % MOISTURE IN STACK GAS BY VOLUME                      8.35
       MOLE FRACTION OF DRY GAS                               0.916
-------------------------------------------------------------------
       % CARBON DIOXIDE                                       5.20
       % OXYGEN                                              15.70
       % CARBON MONOXIDE                                      0.00
       MOLECULAR WEIGHT OF DRY GAS                           29.46
       MOLECULAR WEIGHT OF STACK GAS                         28.50
-------------------------------------------------------------------
       AVERAGE STACK GAS VELOCITY, STACK COND. (MPS)          4.67
       AVERAGE STACK GAS TEMPERATURE (C)                    447.1
       ABSOLUTE STACK GAS PRESSURE (MM HG)                  756.
       STACK GAS FLOW RATE (M3/M)                            46.03
       STACK GAS FLOW RATE (NM3/M)                           17.08
-------------------------------------------------------------------
       NET TIME OF TEST (MIN.)                               60.
       STACK DIAMETER (M)                                     0.457
       SAMPLING NOZZLE DIAMETER (CM)                          1.242
       % ISOKINETIC                                         111.9

       PARTICULATE MASS  PROBE+CYC+FIL (MG)                  39.9
       PARTICULATE MASS TOTAL (MG)                            0.0

       PART. CONC.-FRONT HALF (MG/NM3)                       47.066
       PART. CONC.-TOTAL (MG/NM3)                             0.000
       PART. CONC.-FRONT HALF @ STACK COND. (MG/M3)          17.466
       PART. CONC.-TOTAL @ STACK COND. (MG/M3)                0.000

       EMISSION RATE-FRONT HALF- (KG/HR)                      0.048
       EMISSION RATE-TOTAL- (KG/HR)                           0.000

       F FACTOR ( NM3/10**6BTU)                               0.00
       EMISSION RATE-FRONT HALF- (KG/10**6BTU)                0.000
       EMISSION RATE-TOTAL- (KG/10**6BTU)                     0.000

       % EXCESS AIR                                         302.9
-------------------------------------------------------------------

          STANDARD CONDITIONS  *20 DEG C  *760 MM HG
-------------------------------------------------------------------
                  ENGINEERING SCIENCE INC.
                      ARCADIA, CALIF.
```

```
MC DAVIS PG-PS-1 JULY 14,1981
IMPACTOR FLOWRATE = 0.793 ACFM             IMPACTOR TEMPERATURE =  810.0 F = 432.2 C              SAMPLING DURATION =   1.00 MIN
IMPACTOR PRESSURE DROP = 0.0 IN. OF HG     STACK TEMPERATURE =  810.0 F = 432.2 C
ASSUMED PARTICLE DENSITY = 1.00 GM/CU.CM.   STACK PRESSURE = 0.34 IN. OF HG     MAX. PARTICLE DIAMETER = 100.0 MICROMETERS
GAS COMPOSITION (PERCENT)         CO2 =  7.46        CO =  8.39          N2 = 70.06          O2 =  1.51          H2O = 12.58
CALC. MASS LOADING = 1.1069E+00 GR/ACF       2.6819E+02 GR/DNCF         2.5330E+03 MG/ACM            6.1372E+05 MG/DNCM
IMPACTOR STAGE                               S0       S1       S2       S3       S4       S5                FILTER
STAGE INDEX NUMBER                            1        2        3        4        5        6                  7
D50 (MICROMETERS)                          13.50     8.51     3.99     2.50     1.33     0.65
MASS (MILLIGRAMS)                          34.69     3.21     2.90     1.01     2.55     1.91               10.61
MG/DNCM/STAGE                           3.74E+05 3.46E+04 3.13E+04 1.09E+04 2.75E+04 2.06E+04           1.14E+05
CUM. PERCENT OF MASS SMALLER THAN D50     39.01    33.37    28.27    26.49    22.01    18.65
CUM. (MG/ACM) SMALLER THAN D50          9.88E+02 8.45E+02 7.16E+02 6.71E+02 5.50E+02 4.72E+02
CUM. (MG/DNCM) SMALLER THAN D50         2.39E+05 2.05E+05 1.73E+05 1.63E+05 1.35E+05 1.14E+05
CUM. (GR/ACF) SMALLER THAN D50          4.32E-01 3.69E-01 3.13E-01 2.93E-01 2.44E-01 2.06E-01
CUM. (GR/DNCF) SMALLER THAN D50         1.05E+02 8.95E+01 7.58E+01 7.11E+01 5.90E+01 5.00E+01
GEO. MEAN DIA. (MICROMETERS)            3.69E+01 1.08E+01 5.82E+00 3.20E+00 1.85E+00 9.27E-01           4.57E-01
DM/DLOGD (MG/DNCM)                      4.32E+05 1.71E+05 9.47E+04 5.81E+04 9.56E+04 6.58E+04           3.80E+05
DN/DLOGD (NO. PARTICLES/DNCM)           1.65E+10 2.62E+11 9.19E+11 3.37E+12 2.07E+13 1.58E+14           7.60E+15

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 20 DEG C AND 760MM HG.
AERODYNAMIC DIAMETERS ARE CALCULATED HERE ACCORDING TO MERCER.
```

```
UC DAVIS PG-MS-2 JULY 15,1981
IMPACTOR FLOWRATE = 0,963 ACFM           IMPACTOR TEMPERATURE =  830,0 F = 443,3 C            SAMPLING DURATION =   0,50 MIN
IMPACTOR PRESSURE DROP = 0,0 IN. OF HG   STACK TEMPERATURE =  830,0 F = 443,3 C
ASSUMED PARTICLE DENSITY = 1,00 GM/CU.CM.    STACK PRESSURE = 0,39 IN. OF HG    MAX. PARTICLE DIAMETER = 100,0 MICROMETERS
GAS COMPOSITION (PERCENT)        CO2 =  8,75        CO = 24,06          N2 = 54,28         O2 =  0,41          H2O = 12,50
CALC. MASS LOADING = 8,2947E-01 GR/ACF       1,7780E+02 GR/DNCF        1,8981E+03 MG/ACM          4,0687E+05 MG/DNCM
IMPACTOR STAGE                               S0        S1        S2        S3        S4        S5                FILTER
STAGE INDEX NUMBER                           1         2         3         4         5         6                 7
D50 (MICROMETERS)                           12,37      7,75      3,62      2,35      1,21      0,59
MASS (MILLIGRAMS)                            6,76      2,54      2,35      2,67      3,21      2,77              5,50
MG/DNCM/STAGE                              1,06E+05  3,99E+04  3,69E+04  4,20E+04  5,05E+04  4,35E+04          8,77E+04
CUM. PERCENT OF MASS SMALLER THAN D50      73,88     64,06     54,98     44,67     32,26     21,56
CUM. (MG/ACM) SMALLER THAN D50             1,40E+03  1,22E+03  1,04E+03  8,48E+02  6,12E+02  4,09E+02
CUM. (MG/DNCM) SMALLER THAN D50            3,01E+05  2,61E+05  2,24E+05  1,82E+05  1,31E+05  8,77E+04
CUM. (GR/ACF) SMALLER THAN D50             6,13E-01  5,31E-01  4,56E-01  3,71E-01  2,68E-01  1,79E-01
CUM. (GR/DNCF) SMALLER THAN D50            1,31E+02  1,14E+02  9,70E+01  7,94E+01  5,74E+01  3,83E+01
GEO. MEAN DIA. (MICROMETERS)               3,52E+01  9,79E+00  5,30E+00  2,92E+00  1,69E+00  8,42E-01          4,15E-01
DM/DLOGD (MG/DNCM)                         1,17E+05  1,97E+05  1,12E+05  2,24E+05  1,75E+05  1,30E+05          2,91E+05
DN/DLOGD (NO. PARTICLES/DNCM)              5,14E+09  4,00E+11  1,44E+12  1,72E+13  6,98E+13  4,42E+14          7,81E+15

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 20 DEG C AND 760MM HG.
AERODYNAMIC DIAMETERS ARE CALCULATED HERE ACCORDING TO MERCER.
```

```
HP DAVIS PG-MS-1 JULY 16,1981

IMPACTOR FLOWRATE = 0,989 ACFM              IMPACTOR TEMPERATURE =  835,0 F = 446,1 C              SAMPLING DURATION =   0,50 MIN
IMPACTOR PRESSURE DROP = 0,0 IN, OF HG      STACK TEMPERATURE =  835,0 F = 446,1 C
ASSUMED PARTICLE DENSITY = 1,00 GM/CU,CM,    STACK PRESSURE = 0,45 IN, OF HG     MAX, PARTICLE DIAMETER = 100,0 MICROMETERS
GAS COMPOSITION (PERCENT)          CO2 =  8,81          CO =  0,00          N2 = 76,43          O2 =  0,00          H2O = 14,76
CALC. MASS LOADING = 7,0998E-01 GR/ACF          1,3592E+02 GR/DNCF          1,6247E+03 MG/ACM          3,1103E+05 MG/DNCM
IMPACTOR STAGE                                   S0        S1        S2        S3        S4        S5              FILTER
STAGE INDEX NUMBER                               1         2         3         4         5         6               7
D50 (MICROMETERS)                              12.21      7.65      3.57      2.32      1.19      0.58
MASS (MILLIGRAMS)                               3,28      3,71      2,57      1,57      2,61      3,63             8,38
MG/DNCM/STAGE                                 4,48E+04  5,07E+04  3,51E+04  2,15E+04  3,57E+04  4,96E+04         7,36E+04
CUM. PERCENT OF MASS SMALLER THAN D50         85,50     69,27     57,98     51,08     39,60     23,65
CUM. (MG/ACM) SMALLER THAN D50                1,39E+03  1,13E+03  9,42E+02  8,30E+02  6,43E+02  3,84E+02
CUM. (MG/DNCM) SMALLER THAN D50               2,66E+05  2,15E+05  1,80E+05  1,59E+05  1,23E+05  7,36E+04
CUM. (GR/ACF) SMALLER THAN D50                6,08E-01  4,92E-01  4,12E-01  3,63E-01  2,81E-01  1,68E-01
CUM. (GR/DNCF) SMALLER THAN D50               1,16E+02  9,42E+01  7,88E+01  6,94E+01  5,38E+01  3,21E+01
GEO. MEAN DIA. (MICROMETERS)                  3,49E+01  9,67E+00  5,23E+00  2,88E+00  1,67E+00  8,32E-01         4,09E-01
DM/DLOGD (MG/DNCM)                            4,91E+04  2,50E+05  1,06E+05  1,14E+05  1,24E+05  1,58E+05         2,44E+05
DN/DLOGD (NO. PARTICLES/DNCM)                 2,20E+09  5,28E+11  1,42E+12  9,14E+12  5,12E+13  5,24E+14         6,81E+15

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 20 DEG C AND 760MM HG,
AERODYNAMIC DIAMETERS ARE CALCULATED HERE ACCORDING TO MERCER.
```

```
HC DAVIS SO-CS-3(PE-SO-1) JULY 16,1981

IMPACTOR FLOWRATE = 1.150 ACFM              IMPACTOR TEMPERATURE =  887,0 F = 475,0 C            SAMPLING DURATION =  30.00 MIN
IMPACTOR PRESSURE DROP = 0.1 IN. OF HG      STACK TEMPERATURE =  887,0 F = 475,0 C
ASSUMED PARTICLE DENSITY = 1.00 GM/CU.CM.    STACK PRESSURE = 1.55 IN. OF HG     MAX. PARTICLE DIAMETER = 100,0 MICROMETERS
GAS COMPOSITION (PERCENT)        CO2 =  4.75          CO =  0.00          N2 = 74.88           O2 = 14.42           H20 =  5.95
CALC. MASS LOADING = 1.7448E-02 GR/ACF          9.1423E-01 GR/DNCF          3.9927E+01 MG/ACM          2.0921E+03 MG/DNCM

IMPACTOR STAGE                                     S1        S2        S3        S4        S5                FILTER
STAGE INDEX NUMBER                                  1         2         3         4         5                   6
D50 (MICROMETERS)                                6.77      3.16      2.05      1.06      0.51
MASS (MILLIGRAMS)                                8.30      7.21      4.63      2.35      2,43                4,18
MG/DNCM/STAGE                                3.79E+02  3.29E+02  2.12E+02  1.07E+02  1,11E+02            1,91E+02
CUM. PERCENT OF MASS SMALLER THAN D50           45.42     29.69     19.57     14.44      9.13
CUM. (MG/ACM) SMALLER THAN D50               1.81E+01  1.19E+01  7.81E+00  5.76E+00  3.64E+00
CUM. (MG/DNCM) SMALLER THAN D50              9.50E+02  6.21E+02  4.09E+02  3.02E+02  1.91E+02
CUM. (GR/ACF) SMALLER THAN D50               7.93E-03  5.18E-03  3.41E-03  2.52E-03  1.59E-03
CUM. (GR/DNCF) SMALLER THAN D50              4.15E-01  2.71E-01  1.79E-01  1.32E-01  8.35E-02
GEO. MEAN DIA. (MICROMETERS)                 2,60E+01  4.63E+00  2,55E+00  1.47E+00  7.31E-01            3.58E-01
DM/DLOGD (MG/DNCM)                           3,24E+02  9.96E+02  1.13E+03  3.71E+02  3.48E+02            6.34E+02
DN/DLOGD (NO. PARTICLES/DNCM)                3.51E+07  1.92E+10  1,30E+11  2.22E+11  1.70E+12            2.64E+13

NORMAL (ENGINEERING STANDARD) CONDITIONS ARE 20 DEG C AND 760MM HG.
AERODYNAMIC DIAMETERS ARE CALCULATED HERE ACCORDING TO MERCER.
```

APPENDIX E

COMPUTER PROGRAM LISTING AND INPUT DATA FOR "PAPCOLLCOST" AND "GASFEASSTDY"

A listing of computer programs "PAPCOLLCOST" and "GASFEASSTDY" is included in this appendix. These computer programs were written in the BASIC language for the Commodore PET 2001 mini-computer to analyze the economic feasibility of sludge/wastepaper gasification. The computer program "PAPCOLLCOST" is used to calculate the cost of wastepaper collection. The computer program "GASFEASSTDY" is used to calculate the cost of sludge/wastepaper gasification systems for communities of various sizes. A complete list of the input variables used in both of these programs follows the computer program listing.

```
10 REM    PAPCOLLCOST 10/22/81
11 REM    BY NELSON SOFBO
90 PRINT"⊐"
95 PRINT"▒▒▒▒▒▒"
100 PRINTTAB(4);"COST COMPUTATION PROGRAM FOR THE"
110 PRINT"THE COLLECTION OF SOURCE SEPARATED PAPER"
130 FORI=1TO1000:NEXTI
140 PRINT"⊐"
150 PRINT"  THIS IS A PROGRAM THAT IS USED TO"
151 PRINT"ESTIMATE COSTS OF WASTE PAPER COLLEC-"
152 PRINT"TION IN COMMUNITIES OF DIFFERENT SIZES."
153 PRINT:PRINT"THE PROGRAM IS DIVIDED INTO FIVE PARTS "
154 PRINT:PRINT"1. SOURCE SEPARATED WASTE PAPER COLLEC-"
155 PRINT"   TION COSTS."
156 PRINT:PRINT"2. MSW COLLECTION COSTS WITHOUT WASTE"
157 PRINT"   PAPER COLLECTION."
158 PRINT:PRINT"3. MSW COLLECTION COSTS WITH WASTE"
159 PRINT"   PAPER COLLECTION."
160 PRINT:PRINT"4. SAVINGS DUE TO TIPPING FEE  "
161 PRINT"   REDUCTION."
162 PRINT:PRINT"5. A SUMMARY."
163 PRINT""
164 PRINT""
165 PRINT"WHEN READY TO PROCEEDE WITH THE PROGRAM TYPE 1."
170 INPUT X1
175 IF X1=1GOTO300
180 GOTO90
200 PRINT" "
210 PRINT""
220 PRINT""
230 PRINT""
300 PRINT"⊐"
305 PRINT"1. CALCULATION OF THE SOURCE SEPARATED"
306 PRINT"   WASTE PAPER COLLECTION COSTS
307 PRINT"▒▒▒"
310 PRINT"   ▒SUPPLY THE DATA REQUESTED."
311 PRINT""
312 PRINT"   WHEN READY TO CONTINJE TYPE 1."
313 INPUT"   ";X2
314 IFX2=1GOTO515
315 GOTO90
515 PRINT"⊐"
520 INPUT"MSW GENERATION RATE, LBS/CAP/DAY =";I2
539 PRINT"⊐"
540 INPUT"% COLLECTABLE PAPER IN MSW =";I3
559 PRINT"⊐"
560 INPUT"NUMBER OF PEOPLE PER RESIDENCE =";I4
579 PRINT"⊐"
580 INPUT"PAPER COLL. PICKUP TIME, MIN/RES =";I5
599 PRINT"⊐"
600 PRINT"PAPER COLL. UNLOADING TRANSIT TIME,"
610 INPUT"MIN/ROUND TRIP =";I6
619 PRINT"⊐"
620 PRINT"START & END OF DAY TRANSIT TIME,"
630 INPUT"MIN/DAY/TRUCK =";I7
639 PRINT"⊐"
640 INPUT"TRUCK CAPACITY, TONS/TRIP =";I8
659 PRINT"⊐"
660 INPUT"OFF ROUTE FACTOR, % =";I9
```

```
679 PRINT"⊐"
700 PRINT"MAXIMUM NUMBER OF TRUCK OPERATION"
702 INPUT"HOURS PER COLL. DAY =";J2
719 PRINT"⊐"
720 PRINT"PERCENTAGE OF LABOR COST NECESSARY"
730 INPUT"FOR SUPERVISION AND OVERHEAD =";J3
739 PRINT"⊐"
740 INPUT"INTEREST RATE, % =";J4
759 PRINT"⊐"
760 PRINT"CAPITAL COST OF PAPER COLLECTION"
765 INPUT"TRUCK, $ =";J5
779 PRINT"⊐"
780 PRINT"USEFUL LIFE OF PAPER COLLECTION"
785 INPUT"TRUCK, YEARS =";J6
799 PRINT"⊐"
800 PRINT"SALVAGE VALUE OF PAPER COLLECTION"
810 INPUT"TRUCK, $ =";J7
819 PRINT"⊐"
820 PRINT"PERCENTAGE OF PAPER COLLECTION TRUCK"
825 PRINT"CAPITAL COST FOR MAINTENANCE AND"
830 INPUT"REPAIRS =";J8
839 PRINT"⊐"
840 PRINT"ANNUAL COST OF INSURANCE AND "
845 INPUT"FEES, $/YR/TRUCK =";J9
859 PRINT"⊐"
860 PRINT"FUEL USAGE OF PAPER COLLECTION TRUCK,"
870 INPUT"GAL/HR OF OPERATION =";K1
879 PRINT"⊐"
880 INPUT"FUEL COST, $/GAL =";K4
899 PRINT"⊐"
900 INPUT"COST OF OIL & TIRES, $/HR OPER. =";K2
903 PRINT"⊐"
904 PRINT"LABOR COST INCLUDING FRINGE"
905 INPUT"BENEFITS, $/HR =";J1
906 IFA4=5GOTO1000
908 PRINT"⊐"
909 PRINT"NUMBER OF PERSONS ON PAPER COLLECTION"
910 INPUT"TRUCK CREW =";K5
911 IFA3=4GOTO1000
912 PRINT"⊐":PRINT"PERCENTAGE OF RESIDENCES RECYCLING"
913 INPUT"PAPER =",A1
914 IFA2=3GOTO1000
915 PRINT"⊐" INPUT"SIZE OF COMMUNITY =";I1
916 IFY=2GOTO1000
919 PRINT"⊐"
920 PRINT"PERCENTAGE OF COLLECTABLE PAPER"
930 INPUT"RECYCLED AT EACH RESIDENCE =";K3
1000 A=I1*A1/100/I4/5
1001 REM# OF RESIDENCES COLLECTED PER COLLECTION DAY
2000 B=A*I5/60
2001 REM PICK-UP TIME,CREW-HRS/COLL DAY
3000 C=A*I4*I2*I3/100*K3/100*7/2000
3001 REM PAPER COLLECTED PER DAY,TONS/COLLECTION DAY
4000 D=1
4100 E=C/I8
4200 IFE<=D GOTO 4500
4300 D=D+1
4350 REM # TRIPS/DAY TO UNLOAD
4400 GOTO 4200
4500 F=D*I6/60
4501 REM UNLOADING TIME,CREW-HRS/COLL.DAY
5000 G=1
5001 REM NUMBER OF TRUCKS REQ'D INITIALLY
5100 H=(B+F+G*I7/60)/G
5300 IF H<=J2 GOTO5600
5400 G=G+1
```

```
5401 REM NUMBER OF TRUCKS REQ'D
5500 GOTO5100
5600 J=B+F+G*I7/60
5601 REM TOTAL COLLECTION TIME,CREW-HRS/COLL.DAY
6000 K=J*5*52
6001 REM TRUCK USAGE,HRS/YR
7000 L=K*I9/100*K5
7001 REM LABOR REQUIREMENTS,PERS-HRS/YR
8000 M=L*J1
8001 REM COST OF LABOR,$/YR
9000 N=M*J3/100
9001 REM COST OF SUPERVISION AND OVERHEAD,$/YR
9985 J4=J4/100
9990 P1=J7/((1+J4)↑J6)
9995 P2=(J4*(1+J4)↑J6)/((1+J4)↑J6-1)
 10000 P=(J5-P1)*P2*G
 10001 REM ANNUAL COST OF TRUCK,$/YR
 11000 O=J8/100*J5*G
 11001 REM ANNUAL MAITENANCE COST,$/YR
 12000 R=K*K2
 12001 REM COST OF OIL & TIRES, $/YR
 13000 S=K*K1*K4
 13001 REM COST OF FUEL, $/YR
 14000 T=P+O+R+S+J9*G
 14001 REM TOTAL ANNUAL TRUCK COSTS,$/YR
 15000 U=M+N+T
 15001 REM TOTAL ANNUAL COLLECTION COST,$/YR
 16000 V=C*5*52
 16001 REM TONS PAPER COLL./YR
 17000 W=U/V
 17001 REM COST PER TON COLLESTED, $/TON
 17002 PRINT"J"
 17500 PRINT"COMMUNITY SIZE  ";I1
 17600 PRINT"PAPER RECYCLING PARTICIPATION RATE";A1;"%"
 17700 PRINT"PAPER COLLECTED:";C;"TONS/COLL.DAY"
 17800 PRINT"PAPER COLLECTED:";INT(V);"TONS/YR"
 18000 PRINT"LABOR COST:";INT(M);"$/YR
 19000 PRINT"SUPERVISION & OVERHEAD COST ";INT(N);"$/YR"
 19010 PRINT"TOTAL ANNUAL TRUCK COSTS:";INT(T);"$/YR
 20000 PRINT""
 20001 PRINT"------------------------------------------------------------------------------
"
 20003 PRINT""
 20500 PRINT"TOTAL COLLECTION COSTS,$/YR";INT(U)
 20550 PRINT""
 20600 PRINT"TOTAL COLLECTION COSTS,$/TON";INT(W*100)*.01
 20650 PRINT""
 20700 PRINT"------------------------------------------------------------------------------
----"
 21003 PRINT""
 21100 PRINT"WHEN READY TO CONTINUE TYPE 1."
 21110 INPUTX3
 21120 IFX3=1GOTO21200
 21130 GOTO90
 21200 PRINT"J"
 38000 PRINT"2. CALCULATION OF MSW COLLECTION COSTS"
 38100 PRINT"   W/O WASTE PAPER COLLECTION"
 38500 PRINT""
 38501 PRINT""
 38502 PRINT""
 39000 PRINT"   $ALL VARIABLES EXCEPT THOSE LISTED"
 39001 PRINT"   $ARE ASSUMED TO BE THE SAME AS THOSE"
 39002 PRINT"   $LISTED PREVIOUSLY IN THIS PROGRAM."
 39003 PRINT"   $ONE COLLECTION DAY PER WEEK PER"
 39004 PRINT"   $RESIDENCE IS ASSUMED."
 39005 FORI=1TO2000:NEXTI
```

```
39006 PRINT"J"
39600 IFX=1GOTO42000
39700 IFY=2GOTO42000
39710 IFA2=3GOTO42000
39720 IFA3=4GOTO42000
39730 IFA4=5GOTO42000
40000 PRINT"NUMBER OF PERSONS ON MSW COLLECTION"
40100 INPUT"CREW =";G0
40199 PRINT"J"
40200 INPUT"PICK-UP TIME, MIN/RES =";G1
40399 PRINT"J"
40400 PRINT"UNLOADING TRANSIT TIME."
40500 INPUT"MIN/ROUND TRIP =";G2
40599 PRINT"J"
40600 PRINT"START & END OF DAY TRANSIT TIME."
40700 INPUT"MIN/DAY/TRUCK =";G3
40799 PRINT"J"
40800 PRINT"MSW COLLECTION TRUCK CAPACITY."
40900 INPUT"TONS/TRIP =";G4
40999 PRINT"J"
41000 PRINT"CAPITAL COST OF MSW COLLECTION"
41100 INPUT"TRUCK, $ =";G5
41199 PRINT"J"
41200 PRINT"USEFUL LIFE OF MSW COLLECTION"
41300 INPUT"TRUCK, YEARS =",G6
41399 PRINT"J"
41400 PRINT"MSW COLLECTION TRUCK SALVAGE"
41500 INPUT"VALUE, $ =";G7
41599 PRINT"J"
41600 PRINT"ANNUAL COST OF INSURANCE AND FEES."
41700 INPUT"$/YR/TRUCK =";G8
41799 PRINT"J"
41800 INPUT"FUEL USAGE, GAL/HR-OPER =";G9
41995 REM--------------------------------
42000 H0=I1/I4/5
42100 REM  # RES PER COLL-DAY -----------
42200 H1=H0*G1/60
42300 REM PICK-UP TIME,CREW-HRS/COLL.DAY---------------------------------------
42400 H2=I1*I2*7/5/2000
42500 REM AMT MSW COLL.,TONS/COLL-DAY-------------------------------------------
"
42600 D1=1
42700 E1=H2/G4
42800 IFE1<=D1GOTO43200
42900 D1=D1+1
43000 REM # TRIPS/DAY TO UNLOAD
43100 GOTO42800
43195 REM---------------------------
43200 F1=D1*G2/60
43300 REM UNLOADING TIME,CREW-HRS/COLL-DAY ---------------------------------
43400 D2=1 REM # TRUCKS REQ'D
43500 F2=(H1+F1+D2*G3/60)/D2
43600 IFF2<=J2GOTO43900
43700 D2=D2+1 : REM # TRUCKS REQ'D
43800 GOTO43500:REM------------------
43900 D3=F2*D2
44000 REM TOTAL COLL. TIME, CREW-HRS/COLL-DAY ------------------------------
44100 D4=D3*5*52
44200 REM TRUCK USAGE,HRS/YR -----------------------------
44300 D5=D4*I9/100*G0
44400 REM LABOR REQ'D, PERS-HRS/YR ---------------------------
44500 D6=D5*J1
44600 REM COST OF LABOR, $/YR -------------------------------
44700 D7=D6*J3/100
44800 REM COST OF SUPERVISION AND OVERHEAD, $/YR  -----------------------
44900 REM ANNUAL TRUCK COSTS CALCULATED*
```

```
45000 D8=G7/((1+J4)↑G6)
45100 D9=(J4*(1+J4)↑G6)/((1+J4)↑G6-1)
45200 E2=(G5-D8)*D9*D2
45300 REM ANNUAL TRUCK COSTS,$/YR -------------------------
45400 E3=J8/100*G5*D2
45500 REM ANNUAL MAITENAMCE, $/YR -------------------------
45600 E4=D4*K2
45700 REM OIL & TIRES, $/YR  ------------------------------
45800 E5=D4*G9*K4
45900 REM FUEL COST $/YR ----------------------------------
45950 IF F3=1GOTO50300
46000 E6=E2+E3+E4+E5+G8*D2
46100 REM  TOTAL ANNUAL TRUCK COSTS, $/YR -----------------
46200 E7=D6+D7+E6
46300 REM TOTAL ANNUAL COST,$/YR --------------------------
46400 E8=H2*5*52
46500 REM  TONS MSW COLL/YR ----------- 45950 IF F3=1GOTO50500
46600 E9=E7/E8
46700 REM COST PER TON COLLECTED, $/TON  -----------------
46800 PRINT"J"
46900 PRINT"------------------------------"
46950 PRINT
47000 PRINT"TOTAL ANNUAL MSW COLLECTION COSTS W/O"
47001 PRINT"RECYCLING =",INT(E7),"$/YR"
47100 PRINT""
47200 PRINT"TOTAL MSW COLLECTED W/O RECYCLING ="
47201 PRINTINT(10*E8)/10,"TONS/YR"
47300 PRINT""
47400 PRINT"MSW COLLECTION COSTS W/O RECYCLING ="
47401 PRINTINT(100*E9)/100,"$/TON"
47450 PRINT""
47452 PRINT"------------------------------"
47453 PRINT""
47500 PRINT"WHEN READY TO CONTINUE TYPE 1."
47600 INPUTF4
47700 IF F4=1 GOTO49000
47800 GOTO63000
49000 F3=1
50000 H2=H2-C :REM MSW COLL W/ RECYCLING TONS/COLL-DAY
50100 GOTO42600
50300 F6=E2+E3+E4+E5+G8*D2
50400 REM TOTAL ANN TRUCK COSTS W/ RECYCLING ---------------
50450 F3=0
50500 F7=D6+D7+F6
50600 REM TOTAL ANN COSTS, $/YR W/RECYCLING ----------------
50700 F8=H2*5*52
50800 REM TONS MSW COLL/YR W/ RECYCLING --------------------
50900 F9=F7/F8
51000 REM COST/TON MSW COLLECTED ---------------------------
51001 PRINT"J"
51060 PRINT"3. CALCULATION OF MSW COLLECTION COSTS"
51061 PRINT"   WITH WASTE PAPER COLLECTION."
51070 PRINT""
51090 PRINT"--------------------------------------"
51100 PRINT"TOTAL ANNUAL MSW COLLECTION COSTS WITH"
51101 PRINT"RECYCLING =";INT(F7),"$/YR"
51150 PRINT
51170 PRINT"--------------------------------------"
51200 PRINT"TOTAL MSW COLLECTED WITH RECYCLING"
51201 PRINT" =";INT(F7),"TONS/YEAR"
51250 PRINT""
51300 PRINT"MSW COLLECTION COSTS WITH RECYCLING"
51301 PRINT" =";INT(100*F9)/100,"$/TON"
51350 PRINT""
52000 01=E7-F7
52100 PRINT"ANNUAL MSW COLLECTION COST SAVINGS DUE"
```

```
52101 PRINT"TO RECYCLING OF PAPER =";INT(Q1),"$/YR"
52150 PRINT""
52151 PRINT"----------------------------------------"
52152 PRINT""
52500 PRINT"WHEN READY TO CONTINUE TYPE 1."
52510 INPUTX4
52515 PRINT"J"
52520 IFX4=1GOTO52900
52530 GOTO90
52900 PRINT"J"
53000 PRINT"4. COST SAVINGS DUE TO TIPPING FEE"
53002 FORI=1TO1000:NEXTI
53003 PRINT"J"
53050 IFX=1GOTO54500
53060 IFY=2GOTO54500
53070 IFA2=3GOTO54500
53080 IFA3=4GOTO54500
53090 IFA4=5GOTO54500
53500 INPUT"LANDFILL TIPPING FEES, $/TON =";L3
54500 L8=V*L3
54600 REM ANNUAL LANDFILL TIPPING FEE SAVINGS
54700 L9=L7+L8
54710 PRINT""
54711 PRINT""
54712 PRINT:PRINT"----------------------------------------"
55000 PRINT"ANNUAL LANDFILL SAVINGS ",INT(L9),"$/YR"
55002 PRINT:PRINT"----------------------------------------"
55005 PRINT""
55006 PRINT""
55007 PRINT""
55008 PRINT"WHEN READY TO CONTINUE TYPE 1."
55009 INPUTX5
55010 IFX5=1GOTO55100
55011 GOTO63000
55100 Z1=L9+Q1
55300 Z2=U-Z1
55400 REM NET COST OF PAPER COLLECTION, $/YR
55500 Z3=Z2/V
55600 REM NET COST/TON OF COLL. PAPER
55601 PRINT"J"
55602 PRINT"5. SUMMARY"
55603 PRINT"■■"
55605 PRINT"IF A HARD COPY IS ■NOT■ DESIRED TYPE 1"
55606 INPUTX6
55607 IFX6=1GOTO55615
55610 OPEN3,4
55611 CMD3
55615 PRINT"****************************************************************
****"
55616 PRINT""
55620 PRINT"COMMUNITY SIZE ",I1
55622 PRINT"PERCENTAGE OF RESIDENCES RECYCLING PAPER ",A1
55625 PRINT"PERCENTAGE OF COLLECTABLE PAPER RECYCLED AT EACH RESIDENCE ",K3
55630 PRINT"NUMBER OF PERSONS ON THE PAPER COLLECTION CREW ",K5
55635 PRINT"COST OF LABOR ";J1;"$/HR"
55665 PRINT"WASTE PAPER COLLECTED ",INT(V),"TONS/YR"
55670 PRINT"GROSS WASTE PAPER COLLECTION COSTS ",INT(U);"$/YR "
55671 PRINT"GROSS WASTE PAPER COLLECTION COSTS ";INT(W*100)*.01;"$/TON"
55675 PRINT"COST SAVINGS DUE TO PAPER RECYCLING ";INT(Z1*100)/100
55700 PRINT"NET COST OF PAPER COLLECTION ",INT(Z2),"$/YR"
55800 PRINT"NET UNIT COST OF PAPER COLLECTION ",INT(Z3*100)/100;"$/TON"
55805 PRINT""
55810 PRINT"****************************************************************
****"
55850 IFX6=1GOTO63000
55900 PRINT#3
```

```
55910 CLOSE3
57700 L9=L8
63000 J4=J4*100
63001 F3=0
63005 FORI=1TO4000:NEXTI
63010 X=0:Y=0:A2=0:A3=0:A4=0
63099 PRINT"■■■"
63100 PRINT"IF YOU WANT TO RUN THE PROGRAM AGAIN"
63105 PRINT"CHANGING ONLY THE PERCENTAGE OF COL-"
63200 PRINT"LECTABLE PAPER RECOVERED AT EACH"
63205 PRINT"RESIDENCE, TYPE 1."
63300 INPUTX
63400 IFX=1GOTO919
63500 PRINT"IF YOU WANT TO RUN THE PROGRAM AGAIN CHANGING THE COMMUNITY"
63600 PRINT"SIZE TYPE 2"
63700 INPUTY
63800 IFY=2 GOTO914
63805 PRINT"IF YOU WANT TO RUN THE PROGRAM CHANGING THE % OF THE TOTAL NUMBER"
63806 PRINT"OF RESIDENCES RECYCLING PAPER, TYPE 3"
63807 INPUTA2
63808 IFA2=3GOTO911
63810 PRINT"IF YOU WANT TO RUN THE PROGRAM AGAIN CHANGING THE NUMBER OF PERSONS
"
63811 PRINT"ON THE PAPER COLLECTION CREW TYPE 4"
63812 INPUTA3
63813 IFA3=4GOTO908
63815 PRINT"IF YOU WANT TO RUN THE PROGRAM CHANGING THE COST OF LABOR TYPE 5"
63816 INPUTA4
63817 IFA4=5GOTO903
63820 PRINT"IF YOU DO NOT WANT A HARD COPY OF THE INPUT VARIABLES NOT LISTED AB
OVE"
63821 PRINT"TYPE 6"
63822 INPUTA5
63823 IFA5=6GOTO63900
63824 OPEN3,4
63825 CMD3
63826 PRINT"----------------------------------------------------------------------
----"
63830 PRINT"              INPUT VARIABLES"
63831 PRINT""
63832 PRINT"MSW GENERATION RATE  ";I2;"LBS/CAP/DAY"
63833 PRINT"%COLLECTABLE PAPER IN MSW ";I3
63834 PRINT"NUMBER OF PEOPLE PER RESIDENCE ";I4
63835 PRINT"PAPER COLLECTION PICK-UP TIME ";I5;"MIN/RES"
63836 PRINT"PAPER COLLECTION UNLOADING TRANSIT TIME ";I6;"MIN/ROUND TRIP"
63837 PRINT"PAPER COLLECTION START & END OF DAY TRANSIT TIME ";I7;"MIN/DAY/TRUC
K"
63838 PRINT"PAPER COLLECTION TRUCK CAPACITY ";I8;"TONS/TRIP"
63839 PRINT"OFF-ROUTE FACTOR";I9/100
63840 PRINT"MAXIMUM NUMBER OF TRUCK OPERATION HOURS PER COLLECTION DAY ";J2
63841 PRINT"% LABOR COST NECESSARY FOR SUPERVISION AND OVERHEAD";J3
63842 PRINT"INTEREST RATE,% ";J4
63843 PRINT"CAPITAL COST OF PAPER COLLECTION TRUCK,$";J5
63844 PRINT"USEFUL LIFE OF PAPER COLLECTION TRUCK ";J6;"YEARS"
63845 PRINT"PAPER COLLECTION TRUCK SALVAGE VALUE,$ ";J7
63846 PRINT"%TRUCK CAPITAL COST NECESSARY FOR MAITENANCE & REPAIRS ";J8
63847 PRINT"ANNUAL COST OF INSURANCE AND FEES FOR PAPER COLLECTION TRUCK";J9;"$
63848 PRINT"PAPER COLLECTION TRUCK FUEL USAGE ";K1;"GAL/HR-OPERATION"
63849 PRINT"COST OF FUEL  ";K4;"$/GAL"
63850 PRINT"COST OF OIL & TIRES ";K2;"$/HR-OPERATION"
63851 PRINT"NUMBER OF PERSONS ON MSW COLLECTION CREW ";G0
63852 PRINT"MSW COLLECTION PICK-UP TIME ";G1;"MIN/RES"
63853 PRINT"MSW UNLOADING TRANSIT TIME ";G2;"MIN/ROUND TRIP "
63854 PRINT"MSW START & END OF DAY TRANSIT TIME ";G3;"MIN/DAY/TRUCK"
63855 PRINT"MSW COLLECTION TRUCK CAPACITY ";G4;"TONS/TRIP"
63856 PRINT"CAPITAL COST OF MSW COLLECTION TRUCK,$";G5
```

```
 63857 PRINT"USEFUL LIFE OF MSW COLLECTION TRUCK ",G6;"YEARS"
 63858 PRINT"MSW COLLECTION TRUCK SALVAGE VALUE,$";G7
 63859 PRINT"MSW ANNUAL COST OF INSURANCE AND FEES ",G8;"$/YR/TRUCK"
 63860 PRINT"MSW COLLECTION TRUCK FUEL USAGE ",G9;"GAL/HR-OPERATION"
 63861 PRINT"LANDFILL TIPPING FEE CHARGE ",L3;"$/TON"
 63897 PRINT"-------------------------------------------------------------------
----"
 63898 PRINT#3
 63899 CLOSE3
 63900 PRINT"IF YOU WANT TO RUN THE ENTIRE PROGRAM AGAIN TYPE 3"
 63910 INPUTZ
 63920 IFZ=3 GOTO515
READY.
```

```
 10 REM GASFEASSTDY   11/21/81
 11 REM  BY NELSON SORBO
 895 PRINT"J"
 900 PRINT"              ECONOMIC FEASIBILITY OF"
 901 PRINT"                     GASIFICATION"
 905 FORJ=1TO1000 NEXTJ
 910 PRINT""
 915 PRINT""
 1000 INPUT"COMMUNITY SIZE,PERSONS",A1
 1010 IFP1>0GOTO1645
 1020 INPUT"MAXIMUM ALLOWABLE FUEL ASH CONTENT ,DRY BASIS,%",A2
 1030 IFP1>0GOTO4800
 1060 INPUT"MSW GENERATION RATE,LBS/CAP/DAY ,",A4
 1080 INPUT"PERCENTAGE WASTE PAPER IN MSW,% ",A5
 1090 IFP1>0GOTO4800
 1200 INPUT"PERCENT ASH IN WASTEPAPER,DRY BASIS ",B3
 1210 IFP1>0GOTO4800
 1220 INPUT"PERCENT ASH IN WOODCHIPS,DRY BASIS,",B4
 1230 IFP1>0GOTO4800
 1240 INPUT"PERCENT ASH IN DRY SLUDGE,",B5
 1250 IFP1>0GOTO4800
 1260 INPUT"SLUDGE GENERATION RATE,LB/CAP/DAY DRY SOLIDS",B6
 1280 INPUT"PERCENT SOLIDS IN DEWATERED SLUDGE",B7
 1290 IFP1>0GOTO4800
 1300 INPUT"PERCENT H2OIN WOODCHIPS",B8
 1310 IFP1>0GOTO4800
 1320 INPUT"PERCENT H2O ENTERING DENSIFICATION SYSTEM ",B9
 1330 IFP1>0GOTO4800
 1340 INPUT"PERCENT H2O IN WASTE PAPER ",C1
 1350 IFP1>0GOTO4800
 1360 INPUT"PERCENT H2O IN FUEL ENTERING THE GASIFIER,",C2
 1380 INPUT"NUMBER OF GASIFIER OPERATING HOURS PER DAY,";C3
 1400 INPUT"NUMBER OF GASIFIER OPERATING DAYS PER WEEK,",C4
 1420 INPUT"ENERGY CONTENT OF FUEL ENTERING GASIFIER,BTU/LB",C5
 1430 IFP1>0GOTO4800
 1440 INPUT"GASIFIER HOT GAS EFFICIENTY,%",C6
 1450 IFP1>0GOTO4800
 1460 INPUT"COOLER-CONDENSOR EFFICIENTY,%";C7
 1480 INPUT"PERCENT ENERGY SUPPLIED BY DIESEL FUEL,%",C8
 1490 IFP1>0GOTO4800
 1500 INPUT"BRAKE THERMAL EFFICIENTY OF ENGINE OPERATING W/ PRODUCER GAS,%",C9
 1510 IFP1>0GOTO4800
 1520 INPUT"GENERATOR EFFICIENTY,%";D1
 1540 INPUT"INTEREST RATE,%";A6
 1560 INPUT"NO. OF PERSONS REQ'D FOR W.P. SORTING AND METERING,",A8
 1580 INPUT"WASTE PAPER SORTING RATE,TONS/CREW-HR ",A9
 1600 INPUT"MANUAL LABOR COST, $/HR";B1
 1620 INPUT"PERCENT OF LABOR COST NEEDED FOR ADMIN. AND OVERHEAD,",B2
 1645 FORI=1TO5
 1650 PRINT"WHEN THE % WASTE PAPER COLLECTED IS";I*20;"%"
 1655 INPUT"THE NET ANNUAL COST IN $1000/YR IS";A3(I)
 1660 NEXTI
 1670 IFP1>0GOTO4800
 1680 INPUT"COST OF WOODCHIPS DELIVERED ,$/WET TON";D2
 1690 IFP1>0GOTO4800
 1700 PRINT"THE CAPITAL COST INSTALLED OF A SLUDGE DEWATERING DEVICE TO ACHEIVE
THE"
 1701 INPUT"SOLIDS CONCENTRATION PREVIOUSLY ENTERED IS,$1000",D3
 1720 INPUT"USEFUL LIFE OF SLUDGE DEWATERING DEVICE,YEARS";D4
 1740 INPUT"DOSAGE OF POLYMER NEEDED FOR SLUDGE DEWATERING,LB/DRY TON",D5
 1760 INPUT"COST OF POLYMER,$/LB";D6
 1780 INPUT"% TOTAL CAPITAL COST NECESSARY FOR ANNUAL MAITENANCE",D7
 1800 INPUT"SEMI-SKILLED LABOR COST,$/HR";D8
 1820 INPUT"DEWATERING CAPACITY OF SLUDGE DEWATERING DEVICE,GAL/MIN";D9
 1830 INPUT"SLUDGE SOLIDS CONCENTRATION ENTERING DEWATERING DEVICE,%",E1
 1840 INPUT"TOTAL INSTALLED CAPITAL COST OF DENSIFIER AND SHREDDER,$1000/YR",E2
 1860 INPUT"USEFUL LIFE OF DENSIFIER AND SHREDDER,TONS";E3
 1880 PRINT"TOTAL INSTALLED CAPITAL COST OF DENSIFICATION SYSTEM (EXCLUDING THE"
 1881 PRINT"DENSIFIER AND SHREDDER),INCLUDING WOODCHIP METERING BOX,SLUDGE METER
ING"
 1882 PRINT"BOX,INPUT CONVEYER,MAGNETIC SEPARATION,CYCLONE AND BAGHOUSE,METERING
"
 1883 PRINT"SYSTEM,BUCKET ELEATOR,ELECTRICAL CONTROLS,INSTALLATION,ENGINEERING"
 1884 INPUT"AND CONTENGENCY,$1000 ",E4
 1900 INPUT"CAPITAL COST OF OVERHEAD STORAGE AND DRYING,$/TON",E5
 1920 INPUT"NUMBER OF DAYS DENSIFIER OUTPUT FOR STORAGE AND DRYING",E6
 1940 PRINT"USEFUL LIFE OF THE DENSIFICATION SYSTEM (LESS SHREDDER & DENSIFIER)
 1941 INPUT"AND OVERHEAD STORAGE,YEARS",E7
 1960 PRINT"MAITENANCE,REPAIRS,PARTS,MATERIALS,LABOR,FOR DENSIFICATION SYSTEM"
 1961 INPUT"IN $/TON IS";E8
 1980 INPUT"DENSIFICATION SYSTEM CAPACITY,TONS/HR",E9
 2000 INPUT"POWER REQUIRED FOR MIXING/SHREDDING/DENSIFYING OPERATION,KWH/TON",R1
 2020 INPUT"COST OF POWER,$/KWH",R2
 2025 IFP1>0GOTO4800
 2030 PRINT"SIZE OF DENSIFICATION/GASIFICATION BUILDING FOR 10000 PERSONS OR LES
S"
 2031 INPUT"IN SQUARE FEET",R3
 2040 PRINT"SIZE OF DENSIFICATION/GASIFICATION BUILDING FOR 30000 PERSONS OR LES
S,"
 2041 INPUT"IN SQUARE FEET";R4
 2050 PRINT"SIZE OF DENSIFICATION/GASIFICATION BUILDING FOR MORE THAN 30000 PERS
ONS"
 2051 INPUT"IN SQUARE FEET",R5
 2060 INPUT"UNIT INSTALLED COST OF BUILDING,$/SQR-FT",R6
 2070 INPUT"USEFUL LIFE OF BUILDING,YEARS",R7
 2080 INPUT"% INSTALLED COST FOR ANNUAL BUILDING MAITENANCE,%";R8
 2090 PRINT"TOTAL INSTALLED COST FOR GASIFIER/ENGINE/GENERATOR SYSTEM,$/KW OUTPU
T"
 2091 INPUTR9
 2100 INPUT"USEFUL LIFE OF GAS/ENG/GEN SYSTEM,YEARS",S1
 2110 INPUT"% TOTAL INSTALLED COST NECESSARY FOR ANNUAL MAITENANCE,",S2
 2120 INPUT"% GENERATOR OUTPUT NECESSARY FOR INTERNAL POWER REQUIREMENTS";S3
 2140 S4=C3
 2160 INPUT"COST OF DIESEL FUEL,$/GAL",S5
 2180 INPUT"PERCENTAGE BY WEIGHT OF FUEL THAT IS CONVERTED TO CHAR",S6
 2200 INPUT"BULK DENSITY OF CHAR,LB/FT↑3";S7
 2220 INPUT"CAPACITY OF CHAR DISPOSAL TRUCK,CUBIC YDS";S8
 2230 IFP1>0GOTO4800
 2240 INPUT"DISTANCE TO LANDFILL,MILES",S9
 2260 INPUT"CHAR DISPOSAL TRUCK MILEAGE,MPG",T1
 2280 INPUT"CHAR DISPOSAL TRUCK MAITENANCE, $/MI                    ",T2
 2300 INPUT"AVERAGE SPEED TO LANDFILL,INCLUDING DUMPING,MPH",T3
 2320 INPUT"LANDFILL TIPPING FEE,$/TON",T4
 4800 FORI=1TO5STEP1
 4805 P1=0
 5001 F1(I)=A1*A4*A5*I*20/100*7/5/2000/100
 5021 F2(I)=B6*A1*7/5/2000
 5041 F3(I)=F2(I)/B7*100
 5061 F4(I)=(F3(I)*(1-B7/100-B9/100)+F1(I)*(C1/100-B9/100))/(B9/100-B8/100)
 5081 F5(I)=(F2(I)*(B5-A2)+F1(I)*(1-C1/100)*(B3-A2))/((1-B5/100)*(A2-B4))
 5100 IFF4(I)<F5(I)GOTO5140
 5120 F6(I)=F4(I):GOTO5161
 5140 F6(I)=F5(I)
 5150 IFF6(I)>0GOTO5161
 5155 F6(I)=0
```

```
5161 F7(I)=F1(I)+F3(I)+F6(I)
5181 F8(I)=(F7(I)-(F7(I)*(B9-C2)/100))*2000*5/C4/C3
5201 F9(I)=F8(I)*C5/1000000
5221 G1(I)=F9(I)*C6/100
5241 G2(I)=G1(I)*C7/100
5261 G3(I)=G2(I)*C8/100
5281 G4(I)=(G2(I)+G3(I))*C9/100
5301 G5(I)=G4(I)*D1/100
5321 G6(I)=G5(I)*293.1
5341 G7(I)=G6(I)*C3*C4*52/1000000
5361 G8(I)=F1(I)*260/A9*A8*B1*(1+B2/100)/1000
5381 G9(I)=F6(I)*260*D2/1000
5405 H1=(1+A6/100)↑D4
5410 H2=D3*A6/100*H1/(H1-1)
5416 H3=F2(I)*260*D5*D6/1000
5421 H4=D7/100*D3
5426 H5=B6*A1/E1*100/8.34/D9/60*7/5
5431 H6=H5*260*D8*(1+B2/100)/1000
5436 H7(I)=H2+H3+H4+H6
5470 H8(I)=E3/(F7(I)*260)
5475 IFH8(I)<10GOTO5480
5477 H8(I)=10
5480 H9(I)=A6/100*(1+A6/100)↑H8(I)/((1+A6/100)↑H8(I)-1)
5485 L1(I)=E2*H9(I)
5495 L2(I)=E6*F7(I)*E5/1000
5505 L3(I)=A6/100*(1+A6/100)↑E7/((1+A6/100)↑E7-1)
5510 L4(I)=(L2(I)+E4)*L3(I)
5520 L5(I)=F7(I)*260*E8/1000
5530 L6(I)=F7(I)*260/E9*D8*(1+B2/100)/1000
5540 L7(I)=R1*F7(I)*260*R2/1000
5550 L8(I)=L7(I)+L6(I)+L5(I)+L4(I)+L1(I)
5570 IFA1>10000GOTO5580
5575 L9(I)=R3 GOTO5600
5580 IFA1>30000GOTO5590
5585 L9(I)=R4 GOTO5600
5590 L9(I)=R5
5600 M1(I)=L9(I)*R6/1000
5605 M2(I)=A6/100*(1+A6/100)↑R7/((1+A6/100)↑R7-1)
5615 M3(I)=M2(I)*M1(I)
5625 M4(I)=R8/100*M1(I)
5635 M5(I)=M3(I)+M4(I)
6550 M6(I)=G6(I)*R9/1000
6560 M7(I)=A6/100*(1+A6/100)↑S1/((1+A6/100)↑S1-1)
6565 M8(I)=M6(I)*M7(I)
6575 M9(I)=S2/100*M6(I)
6585 N1(I)=G7(I)*S3/100*R2*1000
6595 N2(I)=S4*C4*52*D8*(1+B2/100)/1000/4
6605 N3(I)=S5*G3(I)/.15*C3*C4*52/1000
6615 N4(I)=N3(I)+N2(I)+N1(I)+M9(I)+M8(I)
6625 N5(I)=G7(I)*R2*1000
6650 N6(I)=F8(I)*S6/100*C3*C4*52/2000
6660 N7(I)=N6(I)*2000/S7/27/S8
6670 N8(I)=S9*2/T3*INT(N7(I)+.5)*B1/1000*(1+B2/100)
6680 N9(I)=S9*2/T1*S5/1000*N7(I)
6690 O1(I)=S9*2*INT(N7(I)+.5)*T2/1000
6700 O2(I)=N6(I)*T4/1000
6710 O3(I)=O2(I)+O1(I)+N9(I)+N8(I)
6805 O4(I)=A3(I)+G8(I)+G9(I)+H7(I)+L8(I)+M5(I)+N4(I)-N5(I)+O3(I)
6815 O5(I)=O4(I)/(F2(I)*5*52)*1000
7000 NEXTI
7500 OPEN3,4
7501 CMD3
7600 PRINT"                          SUMMARY TABLES"
7610 PRINT""
7620 PRINT"CALCULATIONS BELOW ARE BASED ON THE FOLLOWING CRITERIA "
7640 PRINT""
```

```
 7660 PRINT"COMMUNITY SIZE,";A1;"PERSONS"
 7680 PRINT"MAXIMUM ALLOWABLE FUEL ASH CONTENT,";A2;"%"
 7700 PRINT"COST OF DELIVERED WOODCHIPS,";D2;"$/WET TON"
 7720 PRINT"COST OF POWER,";R2;"$/KWH"
 30000 PRINT"-----------------------------------------------------------------------
----"
 30005 PRINT""
 30010 PRINT"                                 ENERGY BALANCE"
 30011 PRINT""
 30012 PRINT"PC=PERCENT OF TOTAL WASTE PAPER COLLECTED"
 30013 PRINT"FI=FUEL INPUT TO GASIFIER,LB/HR"
 30014 PRINT"DI=DIESEL FUEL INPUT, GAL/HR"
 30015 PRINT"KW=ENERGY OUTPUT,KILOWATTS"
 30016 PRINT"WC=QUANITY OF WOODCHIPS NEEDED,TONS/OPERATING DAY
 30017 PRINT""
 30020 PRINT"-----------------------------------------------------------------------
----"
 30021 PRINT" PC       FI          DI          KW          WC"
 30022 PRINT"-----------------------------------------------------------------------
 30025 PRINT#3
 30030 OPEN 1,4,2
 30031 OPEN 2,4,1
 30032 PRINT#1,"999      9999     99.99     9999      999.99"
 30040 FORI=1TO5
 30060 PRINT#2,20*I,F8(I)+.5,G3(I)/.15,G6(I),F6(I)
 30070 NEXTI
 30080 CLOSE2:CLOSE1
 30085 CMD3
 30090 PRINT"-----------------------------------------------------------------------
----"
 30098 PRINT:PRINT:PRINT:PRINT:PRINT
 32100 PRINT"-----------------------------------------------------------------------
----"
 32120 PRINT""
 32140 PRINT"                                 COST SUMMARY"
 32160 PRINT""
 32180 PRINT"THE FOLLOWING ABBREVIATIONS ARE USED IN THE COST SUMMARY TABLES "
 32184 PRINT""
 32185 PRINT"PC= % GENERATED WASTE PAPER THAT IS COLLECTED"
 32190 PRINT"WPC=WASTE PAPER COLLECTION COSTS,$1000/YR"
 32195 PRINT"WPP=WASTE PAPER PROCESSING COSTS,$1000/YR"
 32200 PRINT"WCP=WOODCHIP PROCESSING COSTS,$1000/YR"
 32202 PRINT"SP =SLUDGE PROCESSING COSTS,$1000/YR"
 32205 PRINT"MSD=MIXING/SHREDDING/DENSIFICATION COSTS,$1000/YR"
 32210 PRINT"BLD=DENSIFICATION/GASIFICATION BUILDING COSTS,$1000/YR"
 32215 PRINT"GEG=GASIFIER/ENGINE/GENERATOR COSTS,$1000/YR"
 32220 PRINT"EC= ENERGY CREDIT,$1000/YR"
 32225 PRINT"CD= CHAR DISPOSAL COST,$1000/YR"
 32230 PRINT"NTA=NET TOTAL ANNUAL COST,$1000/YR"
 32235 PRINT"NU= NET UNIT COST,$/TON DRY SLUDGE DISPOSED"
 32240 PRINT""
 32245 PRINT"-----------------------------------------------------------------------
----"
 32250 PRINT" PC        WPC       WPP        WCP         SP        MSD"
 32251 PRINT#3
 32252 OPEN 1,4,2
 32253 OPEN 2,4,1
 32254 PRINT#1,"999      999.9    999.9    9999.9     999.9     999.9   99999.99"
 32255 FORI=1TO5
 32260 PRINT#2,20*I,A3(I),G8(I),G9(I),H7(I),L8(I)
 32265 NEXTI
 32267 CMD3
 32270 PRINT""
 32275 PRINT"-----------------------------------------------------------------------
 32280 PRINT" PC        BLD       GEG        EC          CD      NTA          NU       "
 32285 FORI=1TO5
 32290 PRINT#2,20*I,M5(I),N4(I),N5(I),O3(I),O4(I),O5(I)
 32291 NEXTI
 32292 CLOSE1 CLOSE2
 32293 CMD3
 32295 PRINT""
 32300 PRINT"-------------------------------------------------------------------
----"
 45000 PRINT#3
 45001 CLOSE3
 50000 PRINT""
 50001 PRINT"J"
 50005 PRINT""
 50010 PRINT"A LIST OF VARIABLES IS SHOWN BELOW.  IF YOU WISH TO RUN THE PROGRAM
"

 50011 PRINT"AGAIN BY CHANGING ONLY ONE OF THE VARIABLES SHOWN, TYPE THE NUMBER"
 50012 PRINT"CORRESPONDING TO THE DESIRED VARIABLE.  IF THE DESIRED VARIABLE IS
NOT "
 50013 PRINT"SHOWN TYPE 10 AND ANOTHER LIST WILL BE PRESENTED."
 50015 FORI=1TO1000:NEXTI
 50020 PRINT"J"
 50025 PRINT"VARIABLE LIST 1"
 50030 PRINT"1 COMMUNITY SIZE,PERSONS"
 50035 PRINT"2 MAXIMUM ALLOWABLE ASH CONTENT IN FUEL,%"
 50040 PRINT"3 % ASH IN WASTE PAPER"
 50045 PRINT"4 % ASH IN WOODCHIPS"
 50050 PRINT"5 % ASH IN DRY SLUDGE"
 50055 PRINT"6 % WASTE PAPER IN MSW"
 50060 PRINT"7 % H2O IN WOODCHIPS"
 50065 PRINT"8 % SOLIDS IN DEWATERED SLUDGE"
 50070 PRINT"9 % H2O IN FUEL ENTERING THE DENSIFICAATION SYSTEM"
 50080 INPUT"DESIRED VARIABLE NUMBER,";P1
 50090 ON P1 GOTO1000,1020,1200,1220,1240,1060,1300,1280,1320
 50100 PRINT"J"
 50105 PRINT"VARIABLE LIST 2"
 50110 PRINT" "
 50115 PRINT"1 % H2O IN WASTE PAPER"
 50120 PRINT"2 COST OF DELIVERED WOODCHIPS,$/WET TON"
 50125 PRINT"3 ENERGY CONTENT OF FUEL ENTERING THE GASIFIER"
 50130 PRINT"4 GASIFIER HOT GAS EFFICIENTY"
 50135 PRINT"5 COST OF POWER,$/KWH"
 50140 PRINT"6 % ENERGY SUPPLIED BY DIESEL FUEL"
 50145 PRINT"7 BRAKE THERMAL EFFICIENTY OF ENGINE OPERATING W/ PRODUCER GAS"
 50150 PRINT"8 DISTANCE TO LANDFILL,MILES"
 50160 INPUT"DESIRED VARIABLE NUMBER,";P1
 50170 ON P1 GOTO1340,1680,1420,1440,2020,1480,1500,2240
READY.
```

TABLE E-1

INPUT VARIABLES FOR COMPUTER PROGRAM "PAPCOLLCOST" FOR CALCULATION OF WASTEPAPER COLLECTION COSTS FOR A SLUDGE/WASTEPAPER GASIFICATION SYSTEM

Item	Units	Value
Community size	persons	varies
Percent residences recycling paper (participation rate)	%	varies
Percent collectable paper recycled at each participating residence	%	100
Cost of labor including fringe benefits	$/hour	10
Number of persons on wastepaper collection crew	persons	1
MSW generation rate	lbs/person·day	3.5
Percent collectable paper in MSW	%	33
Number of persons per residence	persons/residence	3.2
Paper collection truck pick-up time	minutes/residence	.5
Transit time to unload paper when paper collection truck full	minutes/round trip	40
Transit time at start and end of day for paper collection	minutes/day·truck	30
Paper collection truck capacity	tons/trip	5.5
Off-route factor	fraction	1.1
Maximum number of truck operation hours per collection day	hours/day	7
Percent labor cost necessary for supervision and overhead	%	25
Interest rate	%	13

TABLE E-1 (continued)

Item	Units	Value
Capital cost of paper collection truck	$	27,000
Useful life of paper collection truck	years	10
Salvage value of paper collection truck	$	6000
Percent truck capital cost necessary for annual maintenance and repairs	%	5.5
Annual cost of insurance and fees for paper collection truck	$/year	2500
Paper collection truck fuel usage	gallon/hour operation	2.38
Cost of fuel	$/gallon	1.25
Cost of oil and tires	$/hour operation	1.50
Number of persons on MSW collection crew	persons/crew	2
MSW collection pick-up time	minute/residence	.5
Transit time to unload MSW when MSW collection truck full	minutes/round trip	40
Transit time at start and end of day for MSW collection	minutes/day•truck	30
MSW collection truck capacity	tons/trip	6.25
Capital cost of MSW collection truck	$	85,000
Useful life of MSW collection truck	years	5
MSW collection truck salvage value	$	17,000
Annual cost of insurance and fees for MSW collection truck	$/yr	3610
MSW collection truck fuel usage	gallon/hour operation	2.38
Landfill tipping fee charge	$/ton	10

MSW = Municipal Solid Waste

TABLE E-2

WASTEPAPER COLLECTION COSTS[a]

Percent of Total Residences Recycling Paper (%)	COMMUNITY SIZE					
	10,000		30,000		50,000	
	Net Total Annual Cost ($1000/yr)	Net Unit Cost ($/ton)	Net Total Annual Cost ($1000/yr)	Net Unit Cost ($/ton)	Net Total Annual Cost ($1000/yr)	Net Unit Cost ($/ton)
20	14.9	35.42	10.8	8.57	-7.5	-3.59
40	15.6	18.58	27.2	10.77	-6.3	-1.50
60	16.4	12.97	27.0	7.13	3.6	.57
80	14.7	8.74	37.8	7.49	15.9	1.89
100	26.4	12.57	37.6	5.96	31.3	2.98

[a] Calculated using computer program "PAPCOLLCOST" and input variables from Table E-1.

TABLE E-3

INPUT VARIABLES FOR "GASFEASSTDY" USED TO CALCULATE COSTS FOR SLUDGE/ WASTEPAPER GASIFICATION SYSTEM

Item	Units	Value
Community size	persons	varies
Maximum allowable fuel ash content	%	5
MSW generation rate	lbs/person•day	3.5
Percent wastepaper in MSW	%	33
Percent ash in wastepaper	%	6
Percent ash in woodchips	%	.5
Percent ash in dry sludge	%	30
Sludge generation rate	lbs/person•day	.112
Percent solids in dewatered sludge	%	30
Percent water in woodchips	%	10
Percent water in fuel entering densification system	%	20
Percent water in wastepaper	%	6
Percent water in fuel entering gasifier	%	10
Number of gasifier operating hours per day	hours/day	20
Number of gasifier operating days per week	days/week	7
Number of gasifier operating weeks per year	weeks/yr	52
Energy content of fuel entering gasifier, LHV, dry basis	BTU/lb	7200
Gasifier hot gas efficiency	%	75
Efficiency of cooler-condensor	%	93

TABLE E-3 (continued)

Unit	Units	Value
Percent energy supplied by diesel fuel	%	15
Brake thermal efficiency of engine operated with producer gas and diesel	%	36
Generator efficiency	%	93
Interest rate	%	13
Number of persons required for sorting and metering of wastepaper	persons	2
Wastepaper sorting rate	tons/crew•hour	3
Cost of manual labor including fringe benefits	$/hour	10
Percent labor cost needed for administration and overhead	%	25
Annual wastepaper collection cost	$1000/year	varies (see Table E-2)
Cost of delivered woodchips	$/wet ton	varies
Belt press capital cost	$/1000	185.2
Useful life of belt press	years	15
Polymer dosage	lb/day•ton sludge	10
Cost of polymer	$/lb	2.50
Percent capital cost needed for annual belt press operation and maintenance	%	5
Semi-skilled labor	$/hour	15
Belt press capacity	gallon/minute	30
Pecent solids entering belt press	%	5

TABLE E-3 (continued)

Item	Units	Value
Total installed capital cost of densifier and shredder	$1000	92.4
Useful life of densifer or shredder	tons (years)	100,000 (10)
Densification system (excluding densifier and shredder) capital cost including installation and contingencies	$1000	92.5
Overhead storage and drying capital costs	$/ton	350
Number of days storage capacity	days	2
Useful life of densification system (excluding densifier and shredder)	years	10
Costs for densification maintenance and repairs	$/ton	2.50
Densificaiton system capacity	tons/hour	6
Power required for mixing, shredding, and densifying	kWh/ton	50
Cost of power	$/kWh	varies
Gasification/densification building requirements for communities of 10,000	ft^2	4000
Gasification/densification building requirements for communities of 30,000	ft^2	5000
Gasification/densification building requirements for communities of 50,000	ft^2	6000
Unit installed cost of building	$\$/ft^2$	15
Useful life of building	years	15
Percent installed cost for building maintenance	%	1
Installed cost of gasifier/engine/generator	$/kW	1000

TABLE E-3 (continued)

Item	Units	Value
Useful life of gasifier/ engine/generator	years	10
Percent installed cost of gasifier/engine/generator for annual maintenance	%	5
Percent generator output for gasifier/engine/generator internal power requirements	%	1
Cost of fuel	$/gallon	1.25
Percent (by weight) fuel converted to char	%	10
Bulk density of char	lb/ft^3	10
Capacity of char disposal truck	yd^3	10
Distance to landfill	miles	10
Char disposal truck mileage	miles/gallon	4.5
Char disposal truck maintenance	$/mile	.30
Average speed (including dumping) to landfill	miles/hour	30
Landfill tipping fee	$/ton	10